Truly, there are lies, brazen lies, and statistics, but let's not, my friends, forget the psychology!

– A. and B. Stroogatskie *"The bug in an ant hill"*, 1979

Reliable Decoding of Neural Data

Yaroslav O. Halchenko[2], Michael Hanke[1]

[1] Dept. of Psychology, University of Magdeburg

RUTGERS
NEWARK

[2] Dept. of Psychology, Rutgers University

Goal of Neuroscience

The task of neural science is to explain behavior in terms of the activities of the brain

Eric Kandel, Principles of Neural science, 4th ed., 2000

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Behavior ——— **Brain Activity**

Means of Investigation

The task of neural science is to explain behavior in terms of the activities of the brain

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Behavior

Response time

Accuracy

. . .

Brain Activity

Extracellular Recordings

Electroencephalography (EEG)

Magnitoencephalography (MEG)

Functional Magnetic Resonance Imaging (fMRI)

. . .

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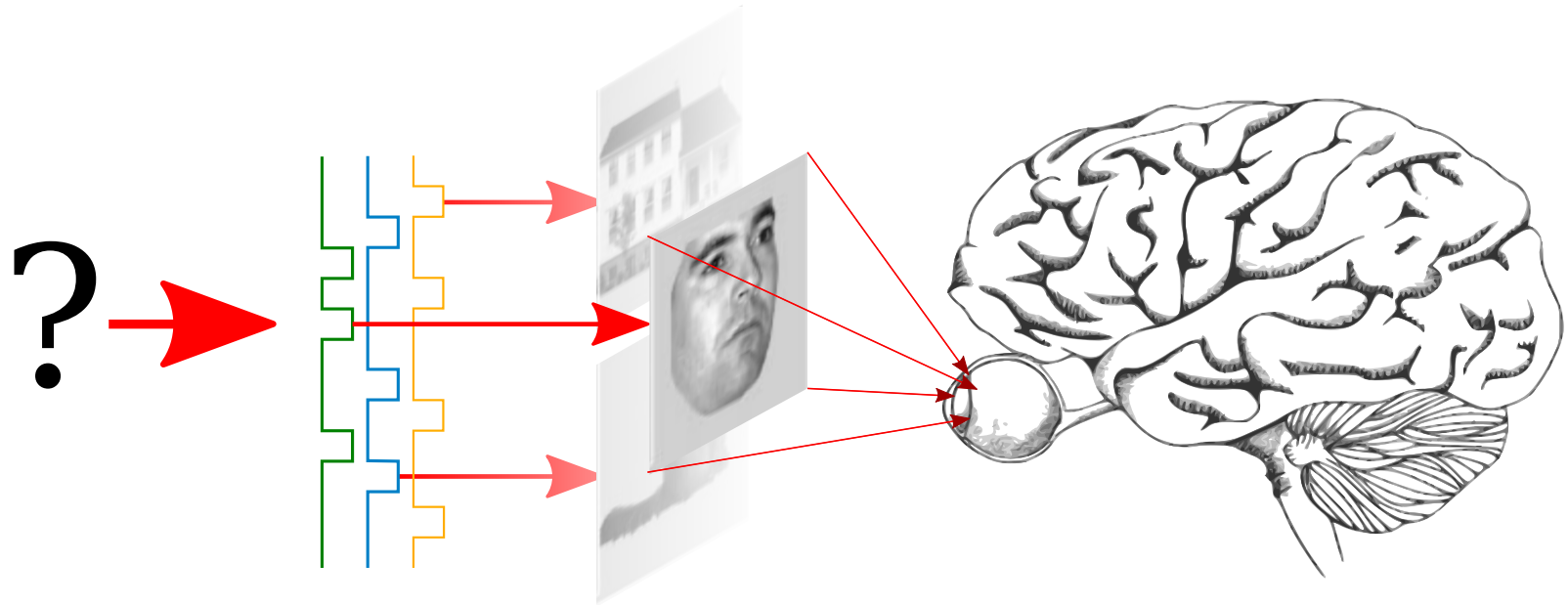
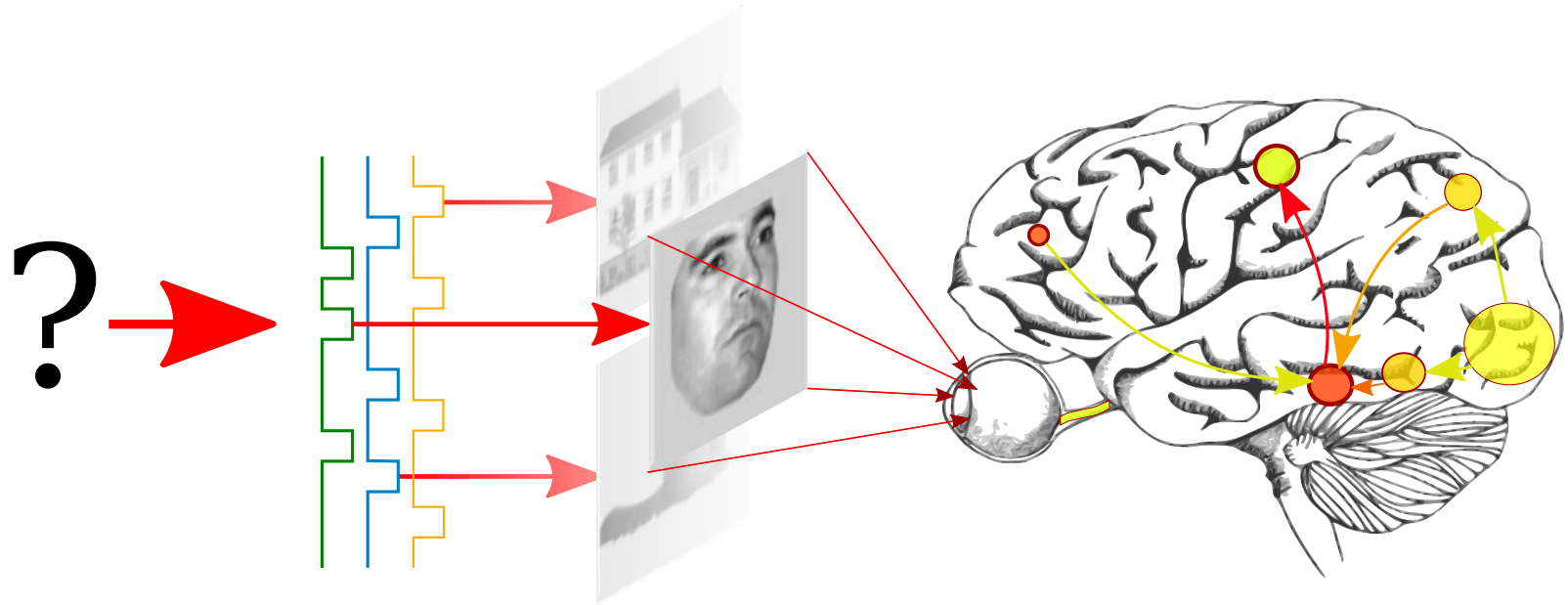
Behavior ⇒ Neural Activity



Behavior ⇒ Neural Activity



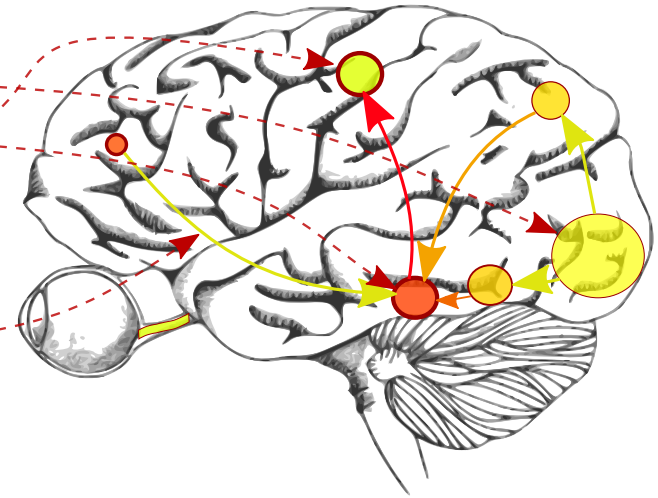
Goals

Localization

- *Early visual perception*
- *Object recognition*
- *Motor response*
- . . .

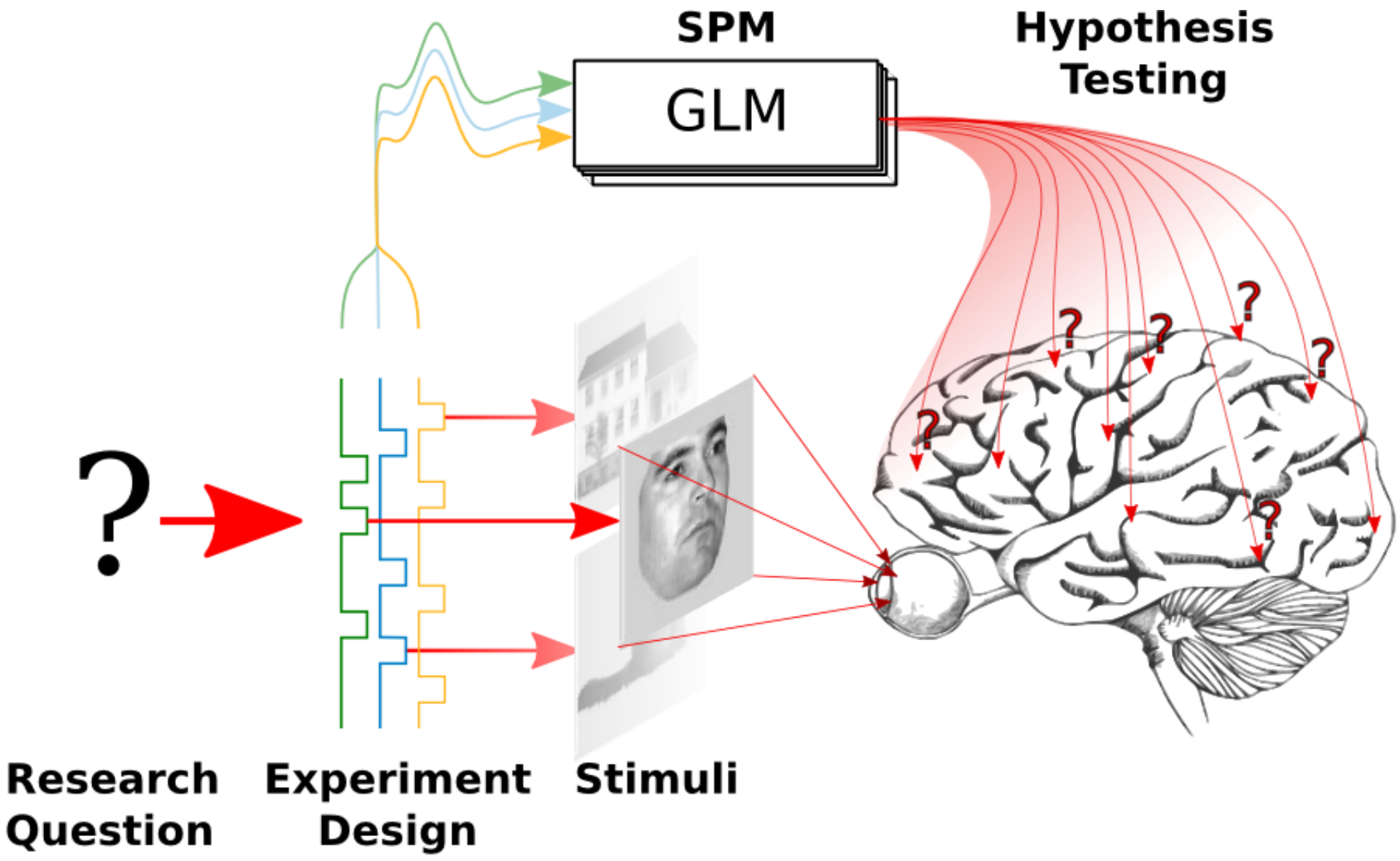
Information flow

- *Attention*
- *Executive control*
- *Inhibition*
- . . .

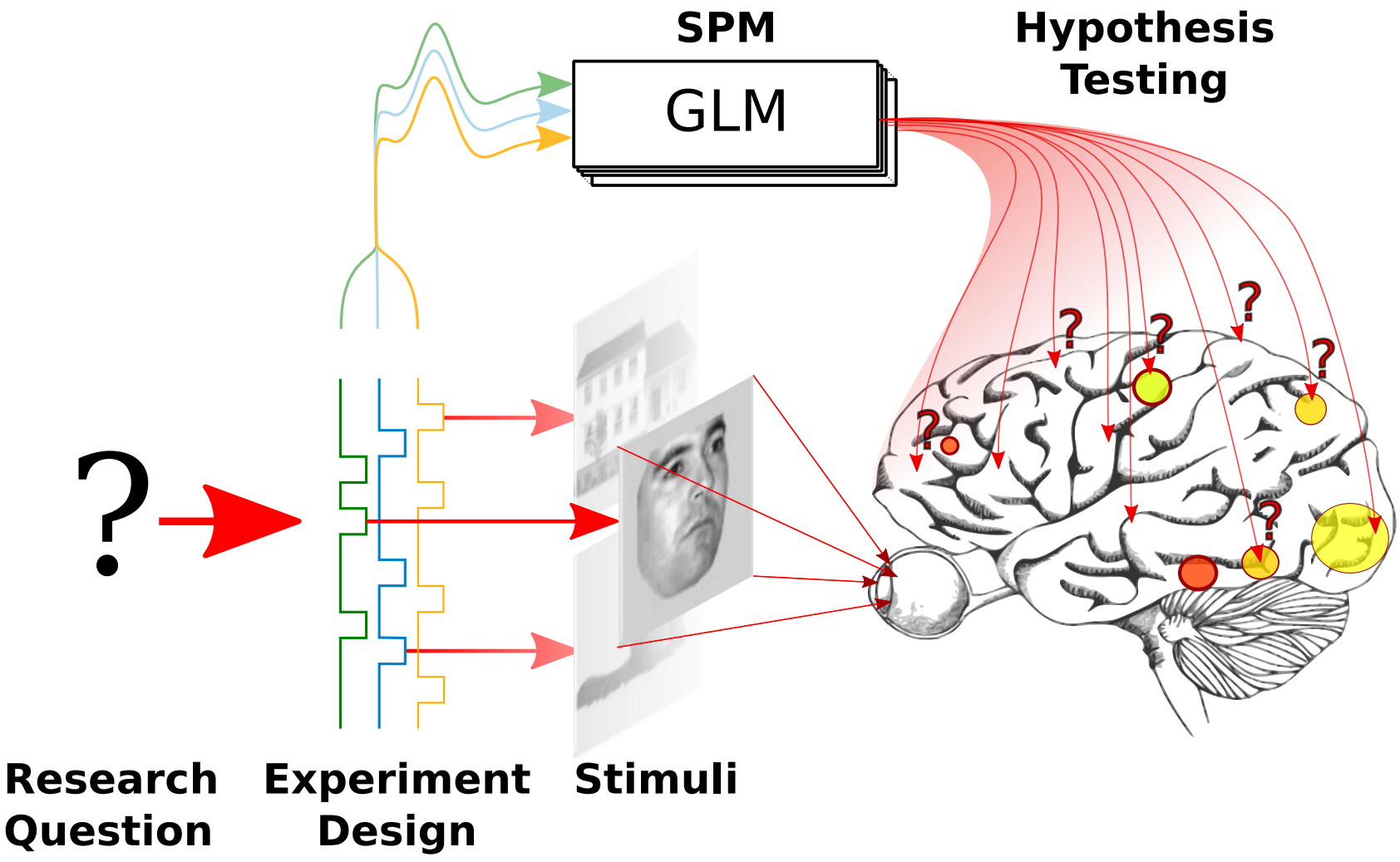


Neural Processing and Encoding

SPM via GLM


SPM
GLM
Hypothesis
Testing
?
Research
Question
Experiment
Design
Stimuli

SPM via GLM


SPM
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Limitations

- Carry no validity testing (not cross-validated)
- Are mass-univariate
- Do not care about cross-trial variance
- Account neither for not-controlled sources of variance, nor covariance/causal structure
- Rely on restrictive assumptions (forward EEG/MEG/BOLD model)
- Obliterate the information through averaging and/or spatial smoothing

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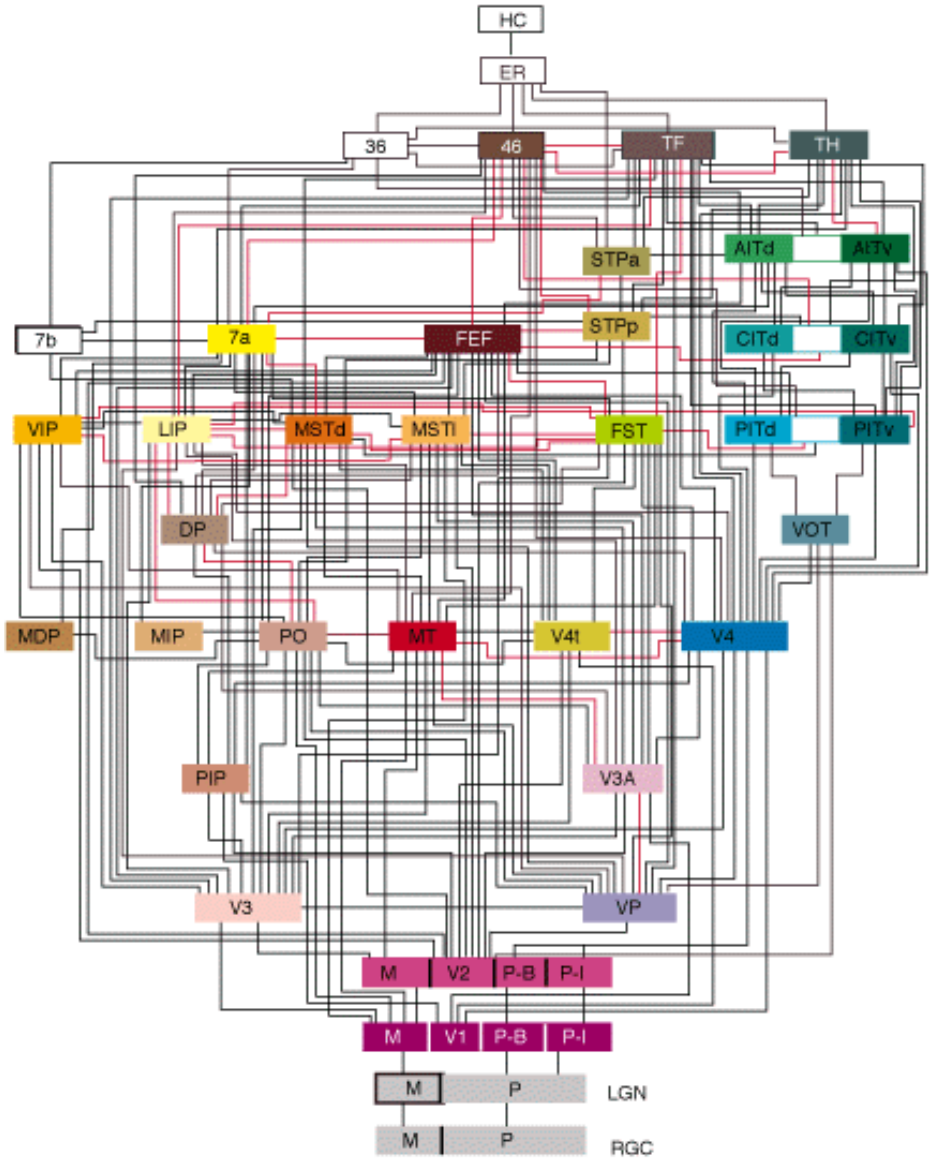
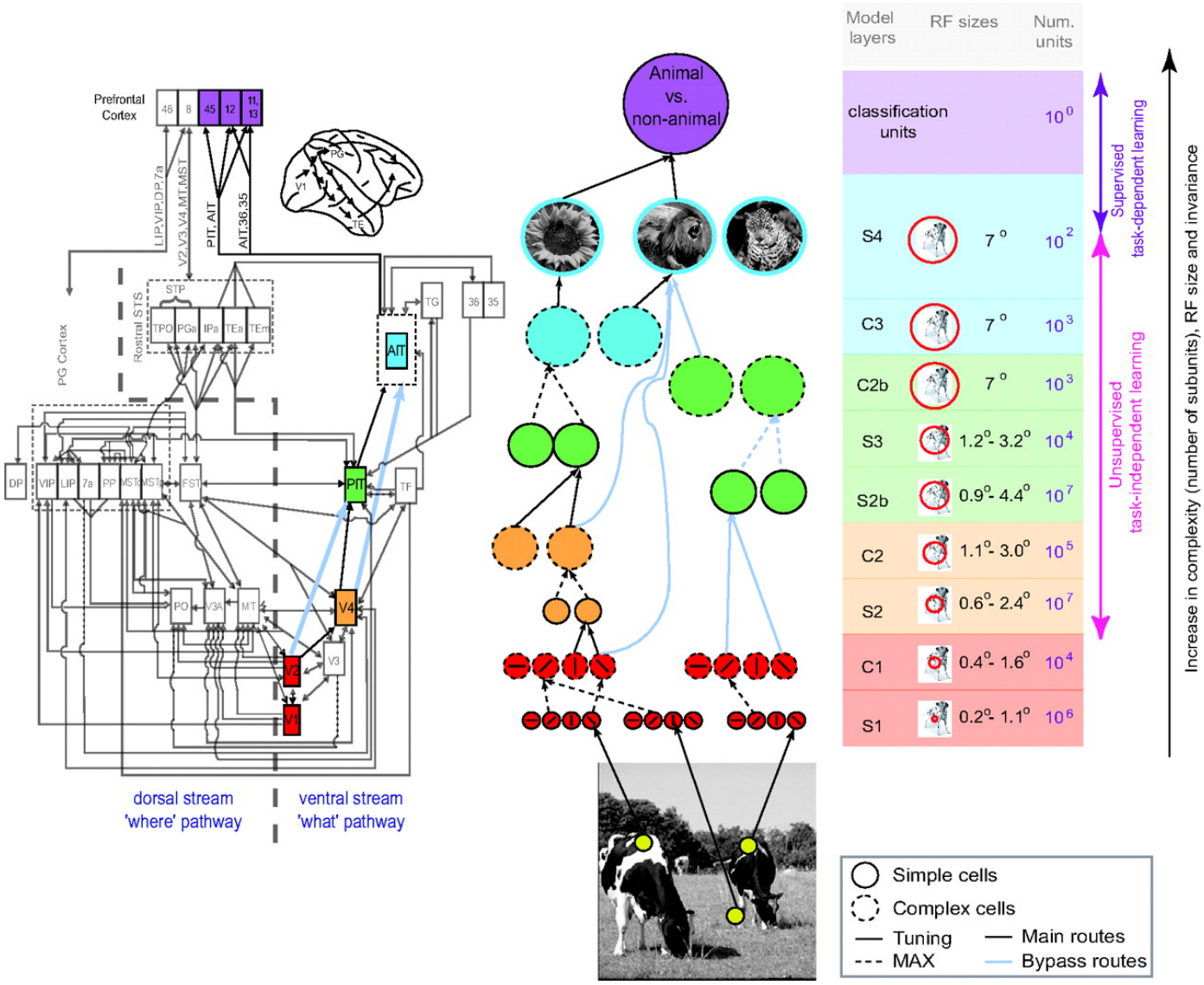
- Rely on restrictive assumptions (forward EEG/MEG/BOLD model)
- Obliterate the information through averaging and/or spatial smoothing
- Are behavior-based models ignorant of the brain structure
- Are confirmatory approaches dragged into solving exploratory problems

Known Organization of the Visual System



Van Essen et al. (1992)

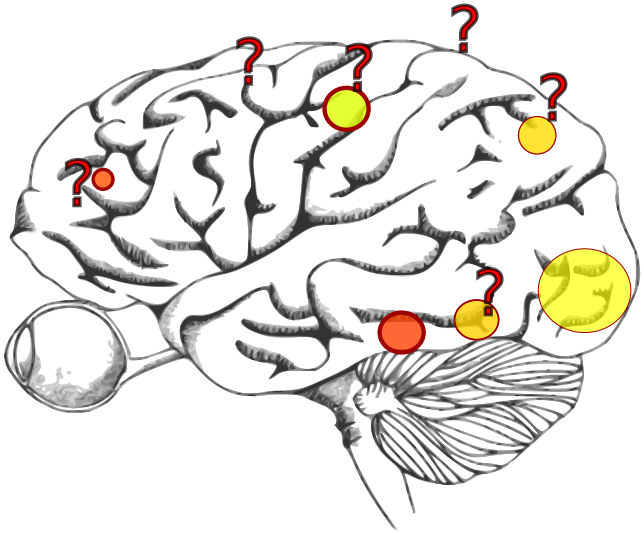
Model of the Visual System

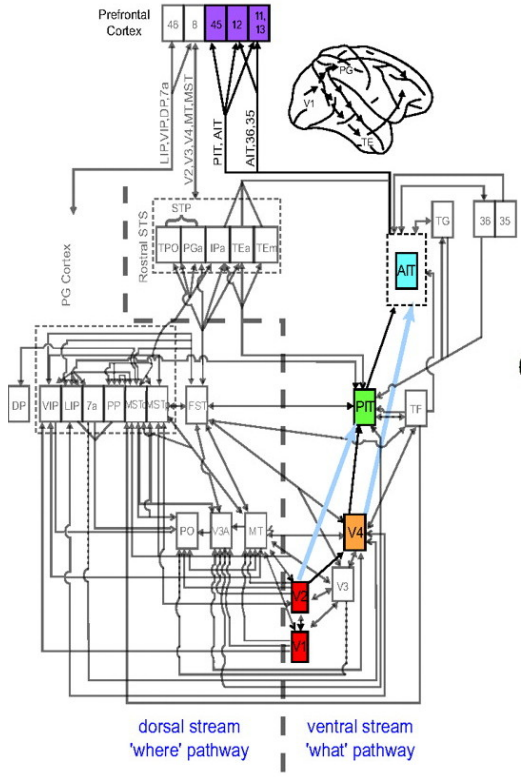


Serre et al. (2007)

From Blobology to Models

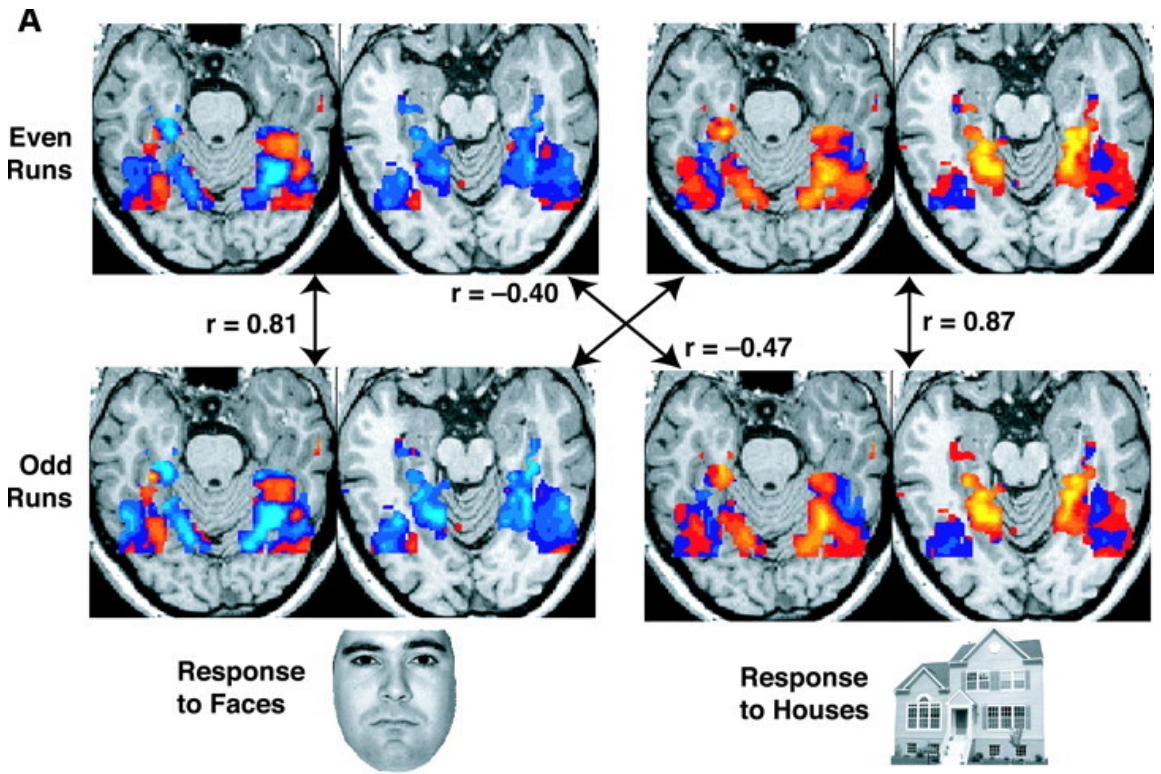
GLM ⟷ Models

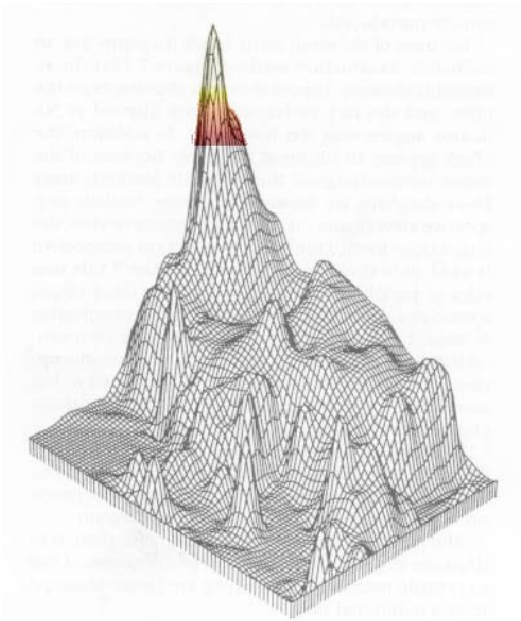




From Blobology to Models

GLM ← MVPA → Models

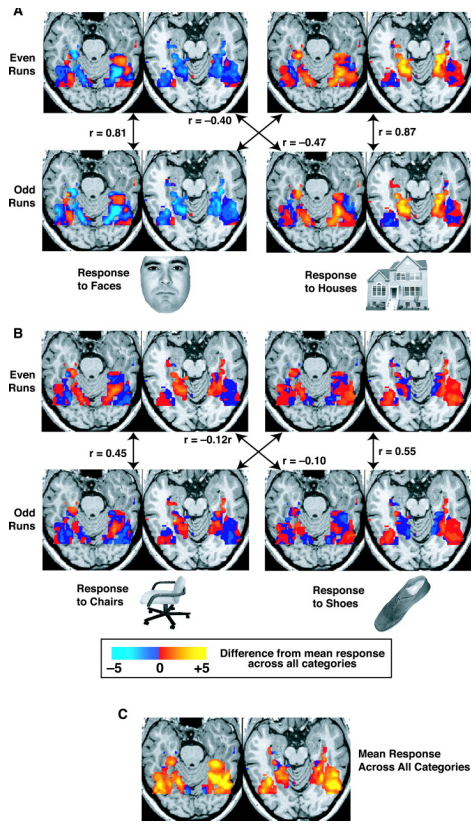


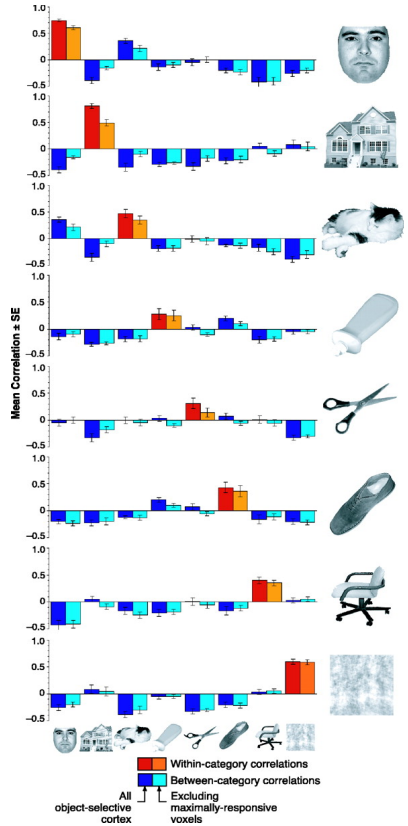


Haxby et al. (2001)

From Blobology to Models

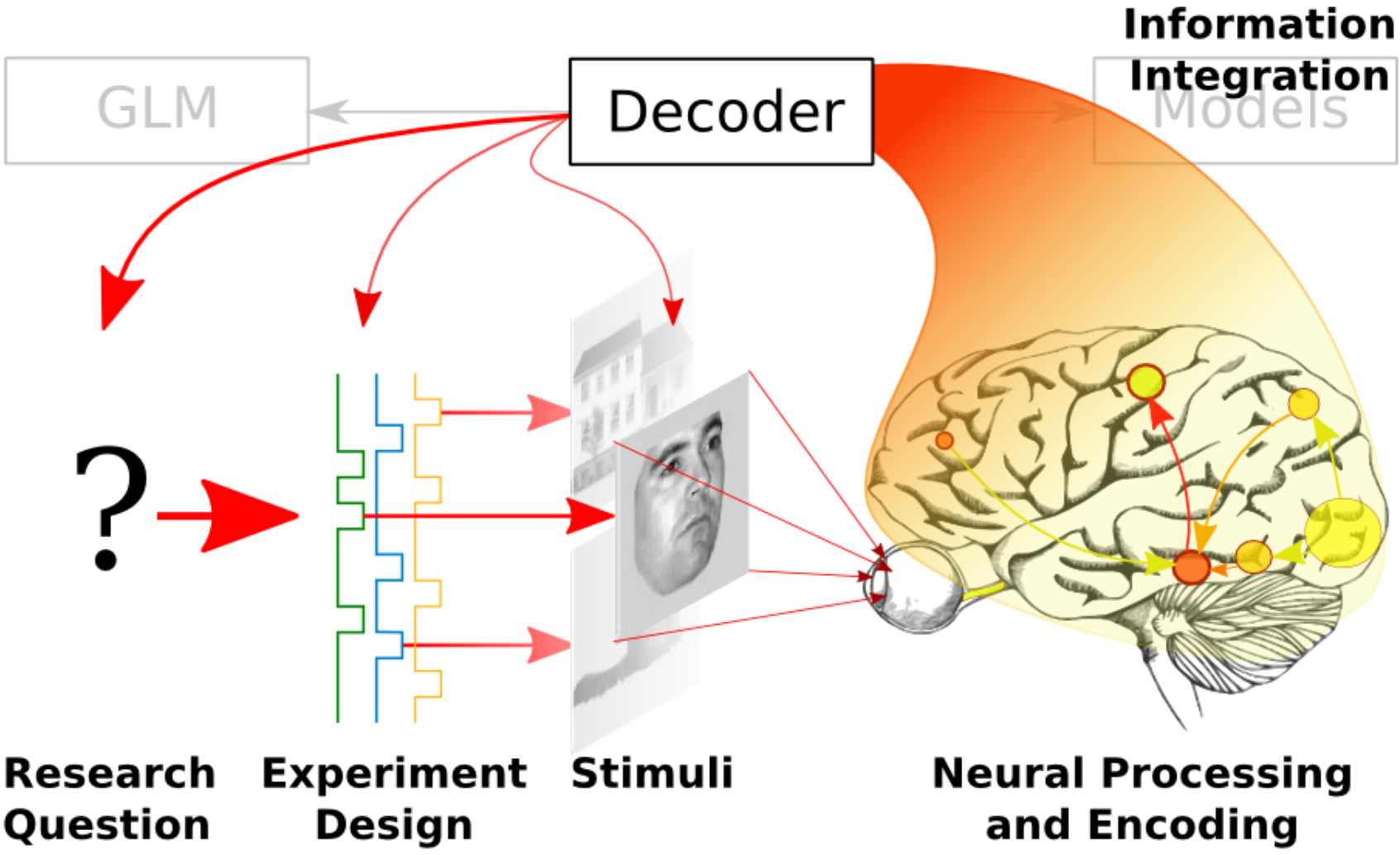
GLM ← MVPA Decoder → Models



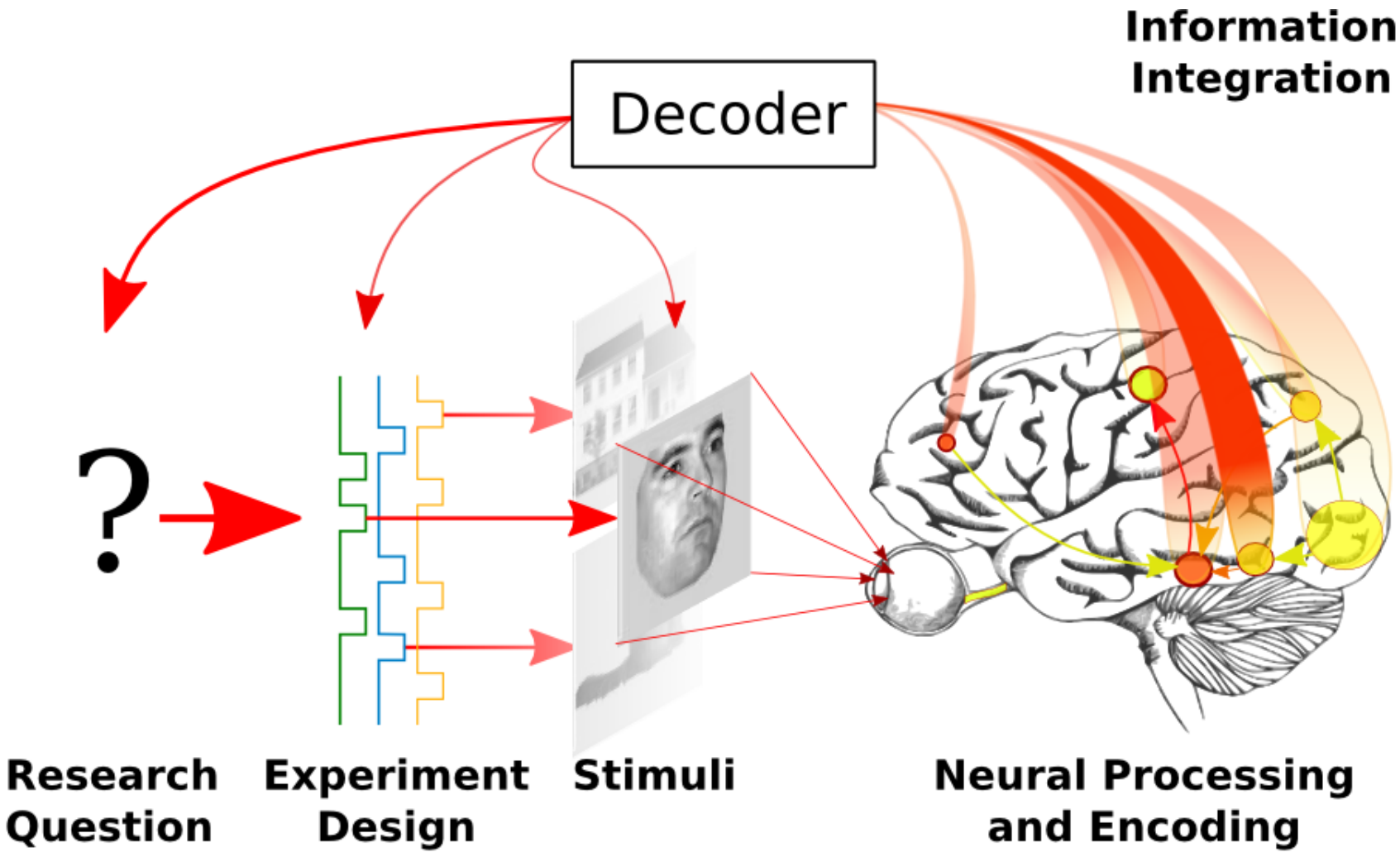


Haxby et al. (2001)

Decoding Approach: Reverse the Flow!



Decoding Approach: Analysis



Decoding Approach...

- Is data modality neutral
- Could incorporate the models of the brain functioning
- Is driven by the data, not by the assumptions
- Is capable of per-trial analysis
- Provides validity testing (cross-validation)
- Accounts for various sources of variance and covariance/causal structure (Sato et al., 2008)
- Relaxes modeling assumptions of the signals

Decoding Approach...

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- Provides validity testing (cross-validation)
- Accounts for various sources of variance and covariance/causal structure (Sato et al., 2008)
- Relaxes modeling assumptions of the signals
- Provide super-acuity effect (Kamitani & Tong, 2005)

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Response time

Accuracy

. . .

Brain Activity

Extracellular Recordings

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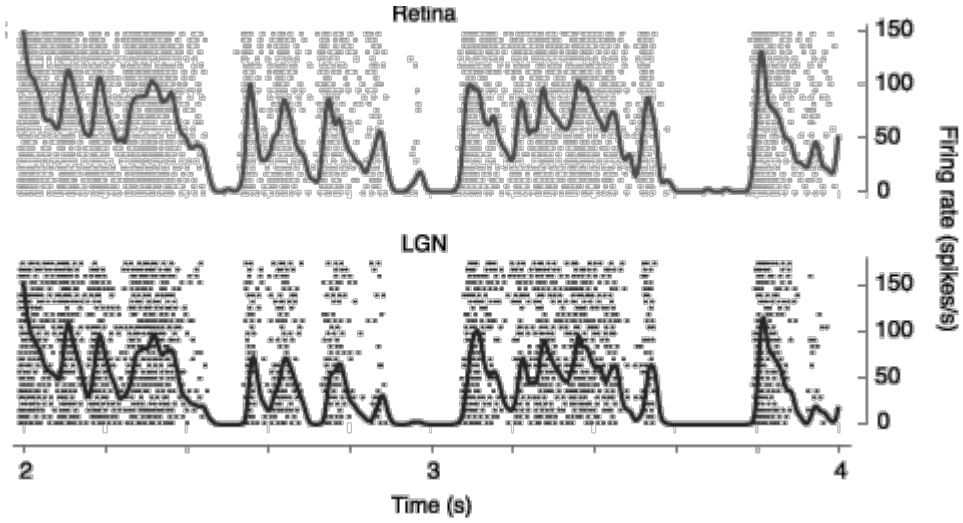
Extracellular Recordings



Brain Activity

Temporal Resolution:	High
Spatial Resolution:	None
Invasive:	Yes
Direct Measurement:	Yes

Extracellular Recordings

Electroencephalography (EEG)

Magnitoencephalography (MEG)

Functional Magnetic Resonance Imaging (fMRI)

. . .

Extracellular Recordings

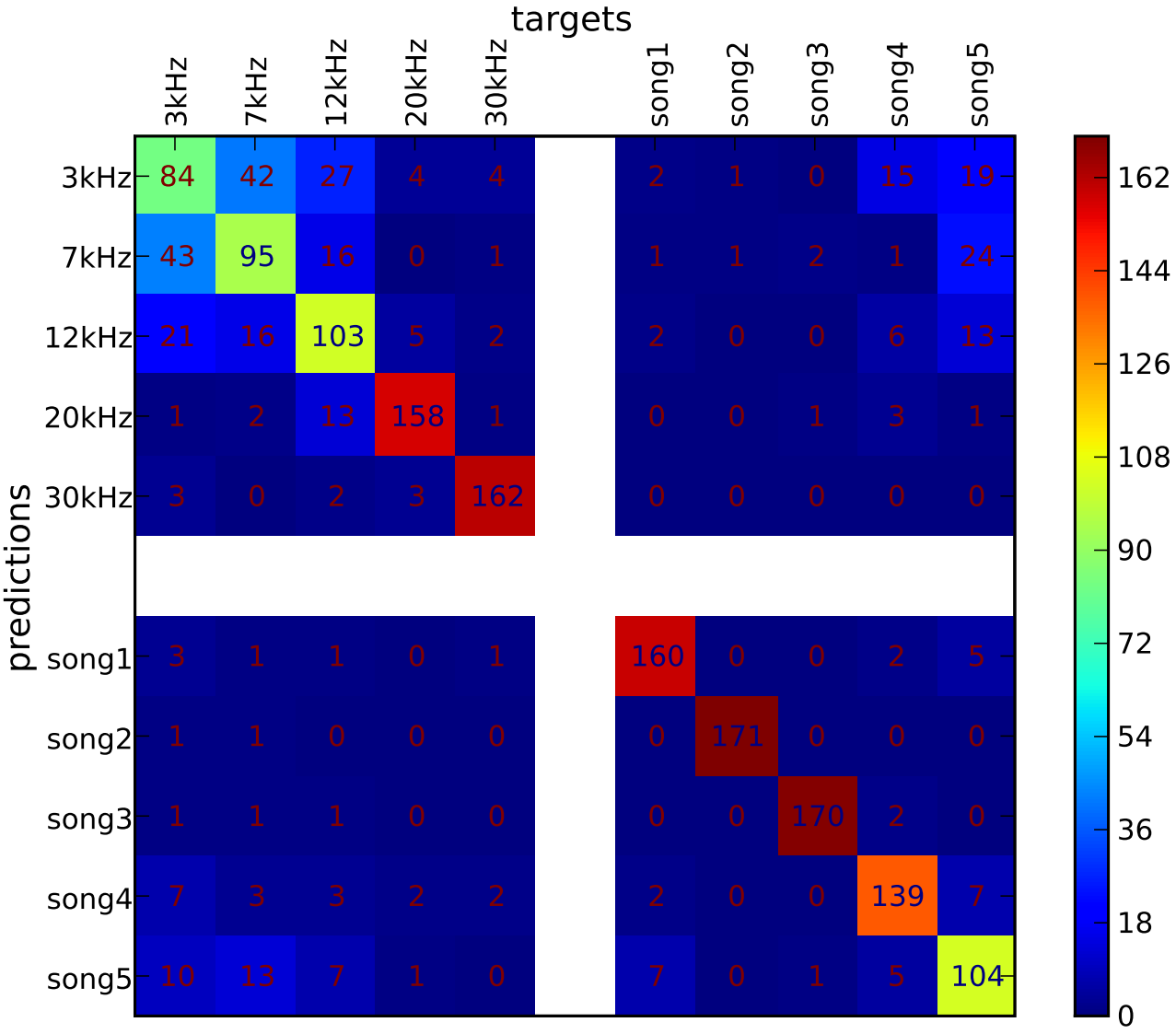
Experiment

- Auditory experiment (Thanks Dr. A. Luczak, Dr. K.D. Harris)
  - Five pure tones (3, 7, 12, 20, 30 kHz)
  - Five different natural sounds
- Animal research: rat
- Eight four-site recording shanks
- 105 units (neurons)

Goal

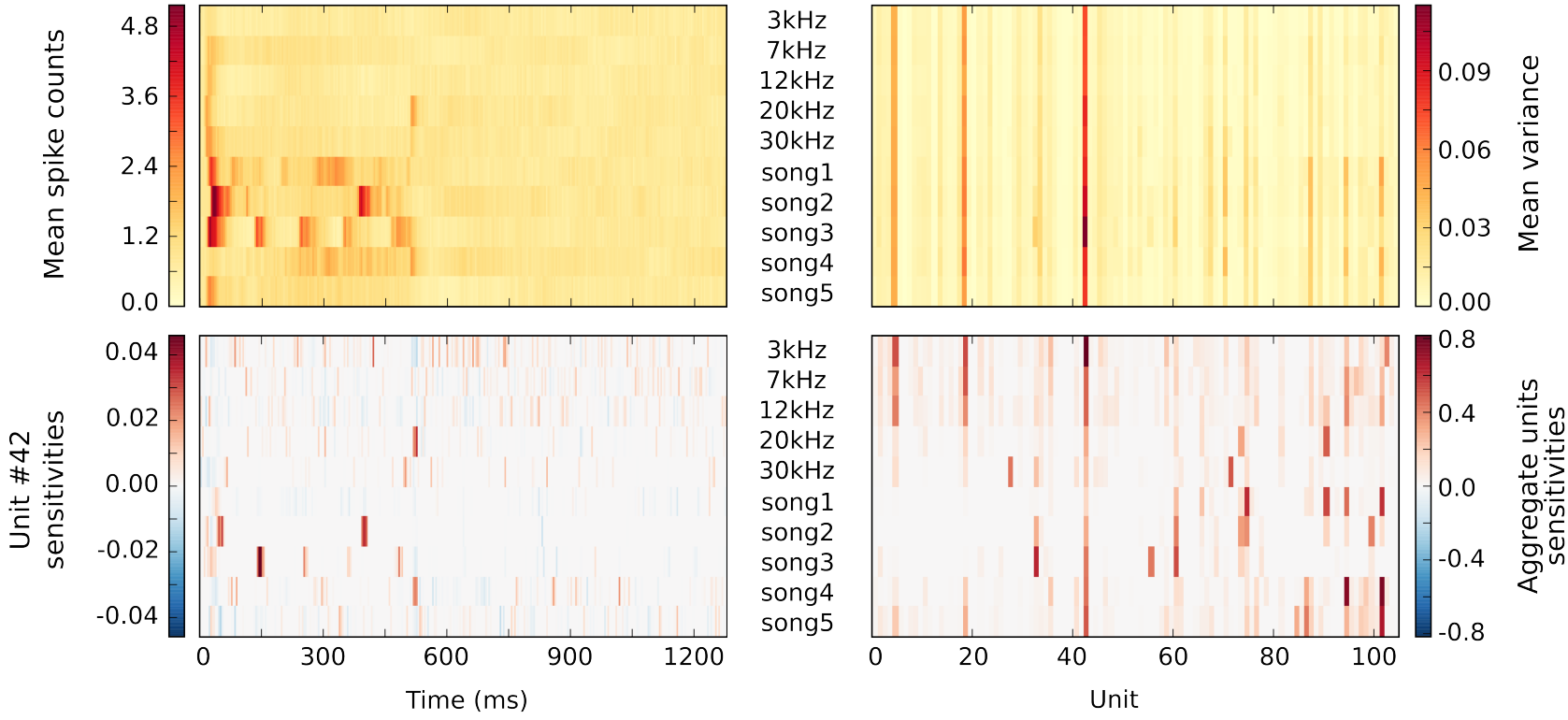
- Confirm relevance of the recorded neural population to auditory processing
- Assess relevance of each neuron toward processing of specific auditory stimulus

Decoding: SMLR



Hanke et al. (2009)

Sensitivity Analysis



EEG/MEG

EEG

MEG

Brain Activity

Temporal Resolution:	High
Spatial Resolution:	Low
Invasive:	No
Direct Measurement:	Yes

Extracellular Recordings

Electroencephalography (EEG)

Magnitoencephalography (MEG)

Functional Magnetic Resonance Imaging (fMRI)

. . .

EEG

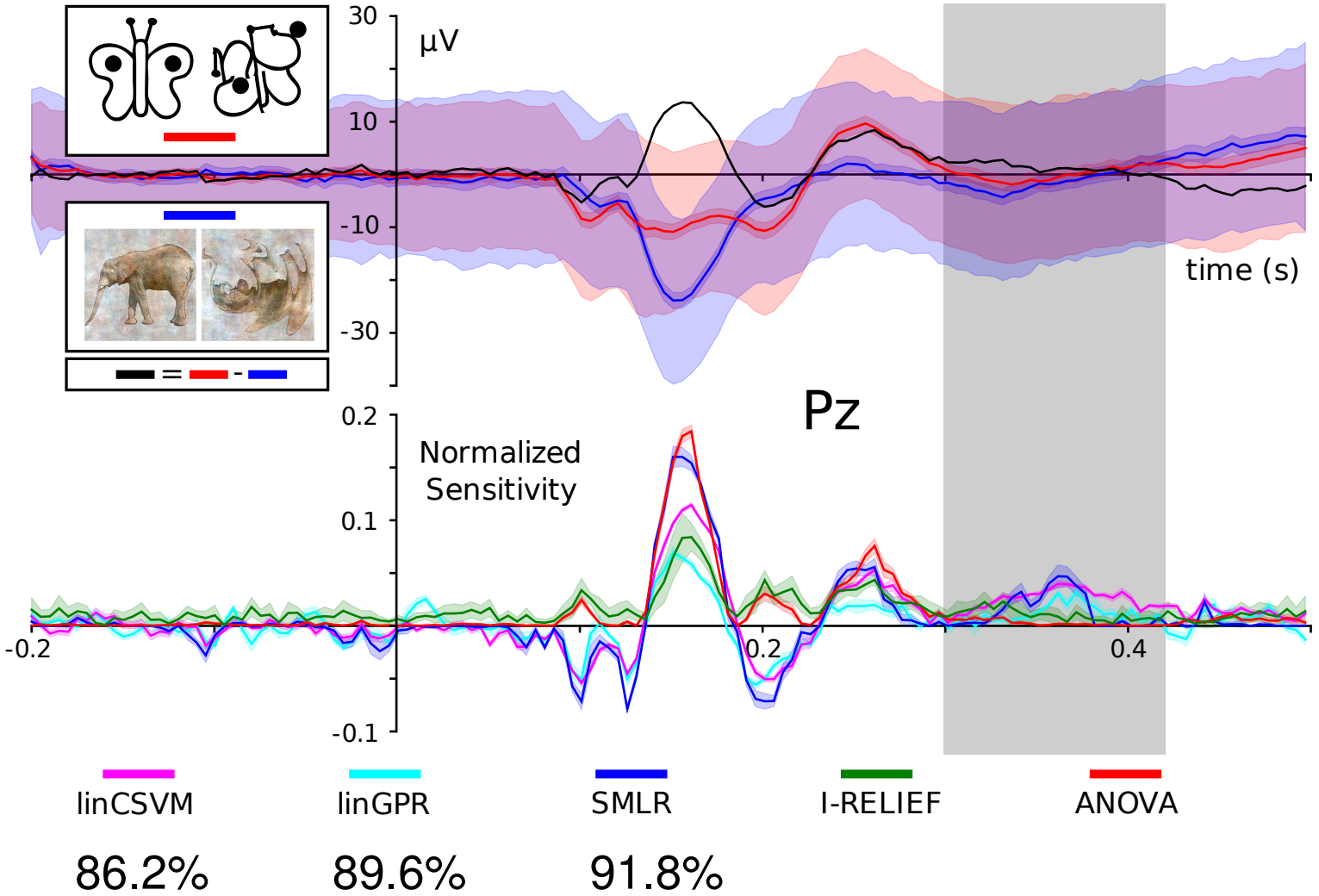
Experiment

- Cognitive modality: visual processing
- Data from Fründ et al. (2008)
- Experimental task: meaningful vs “object-like”
- Analysis task: colored vs line-art
- 852 trials
- 140 time samples per trial, 31 EEG electrode

Goals

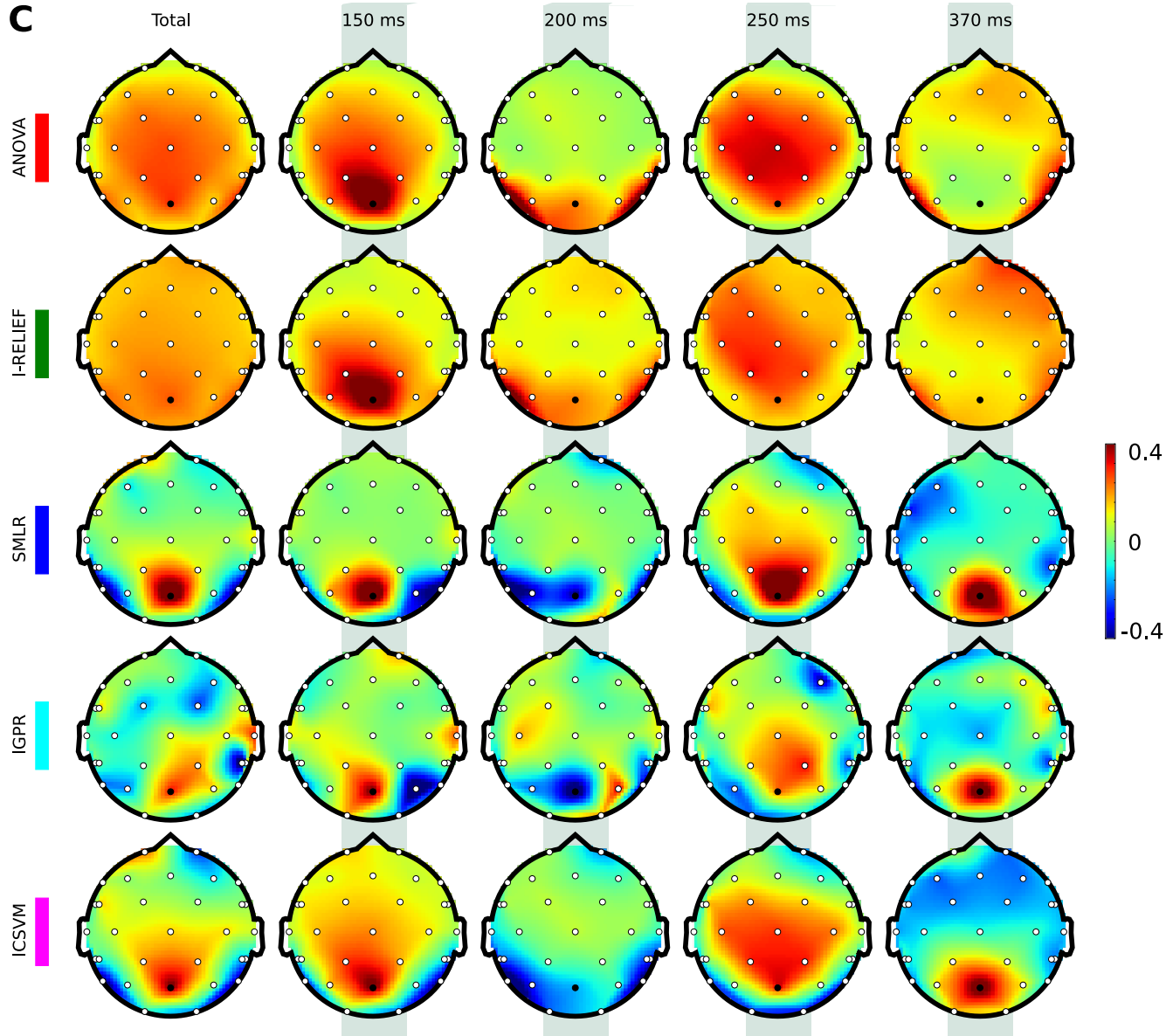
- Achieve reliable per-trial analysis of EEG data
- Confirm results of the conventional analysis
- Show advantages of the decoding approach

EEG: *Pz* Electrode



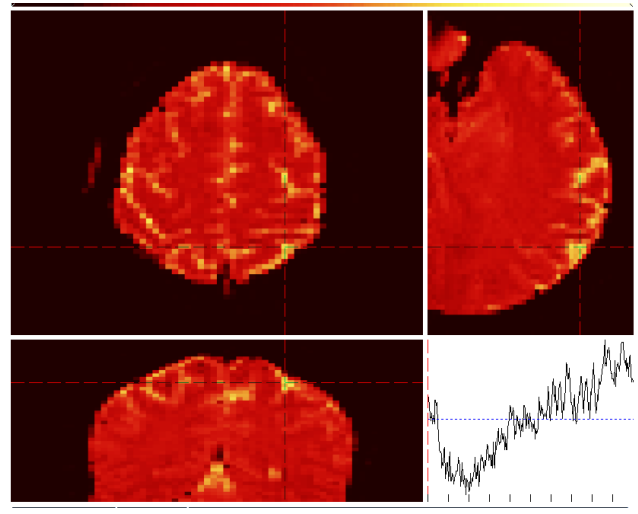
Hanke et al. (2009)

EEG: Temporal Profile



Hanke et al. (2009)

Functional MRI (fMRI)



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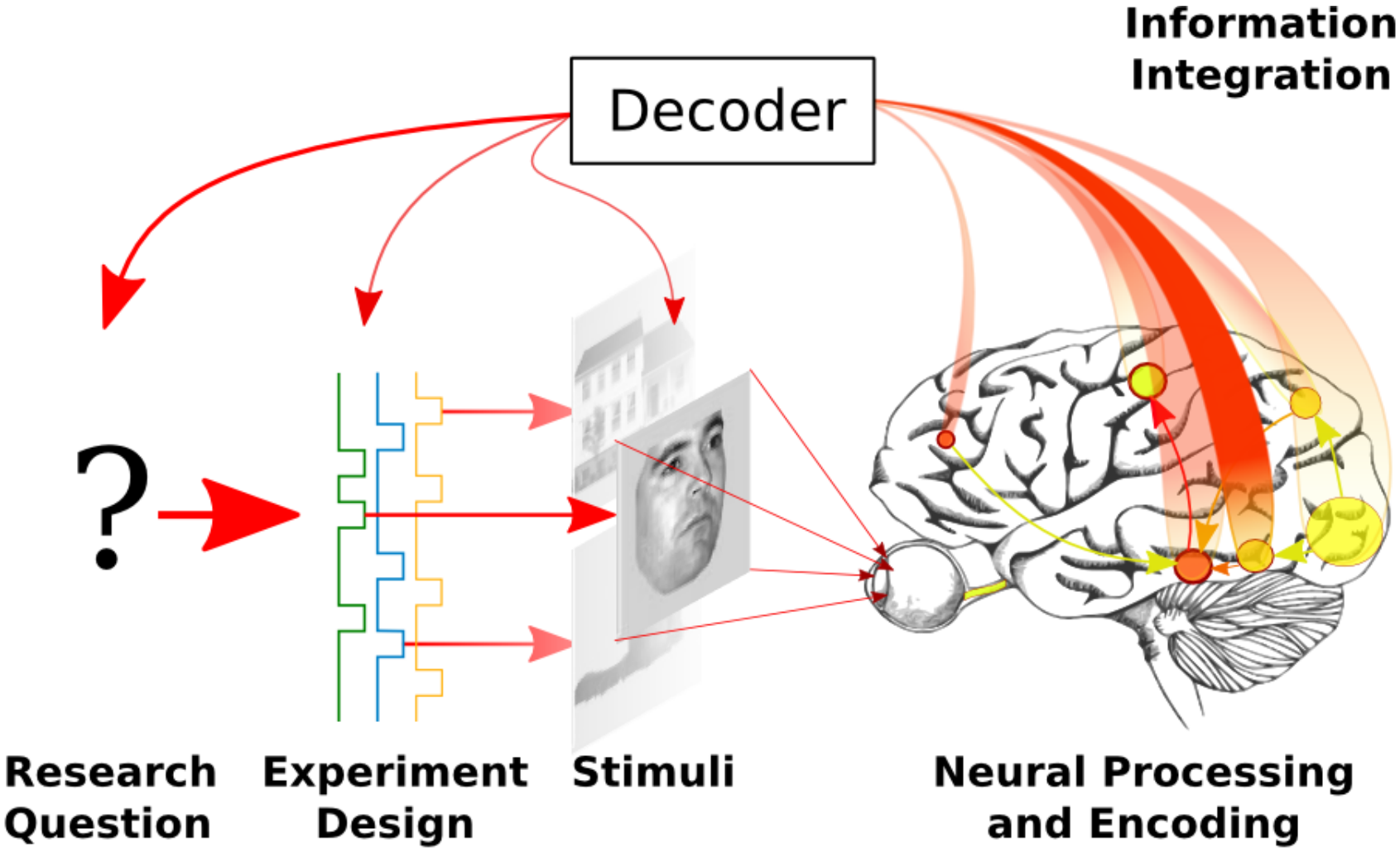
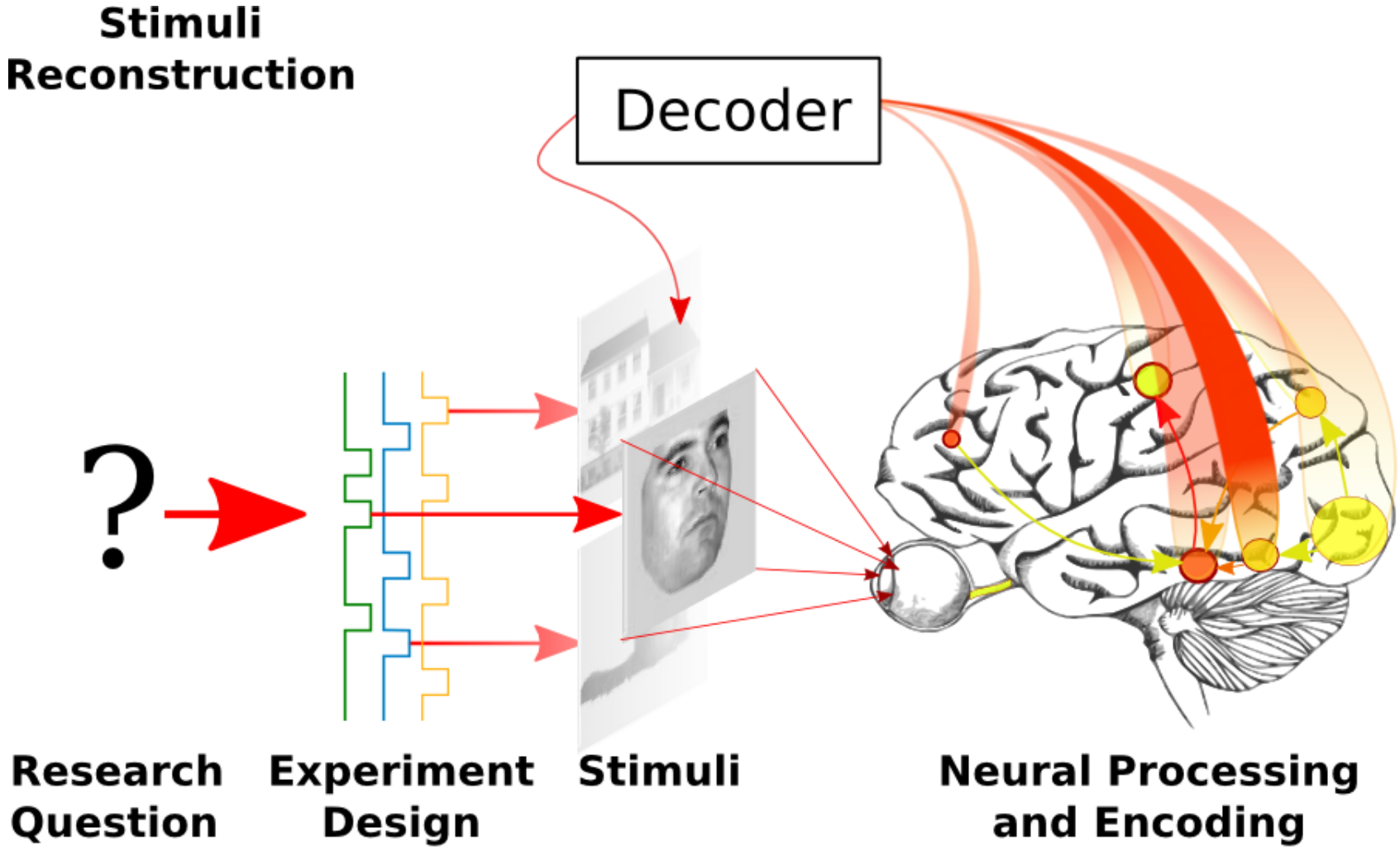
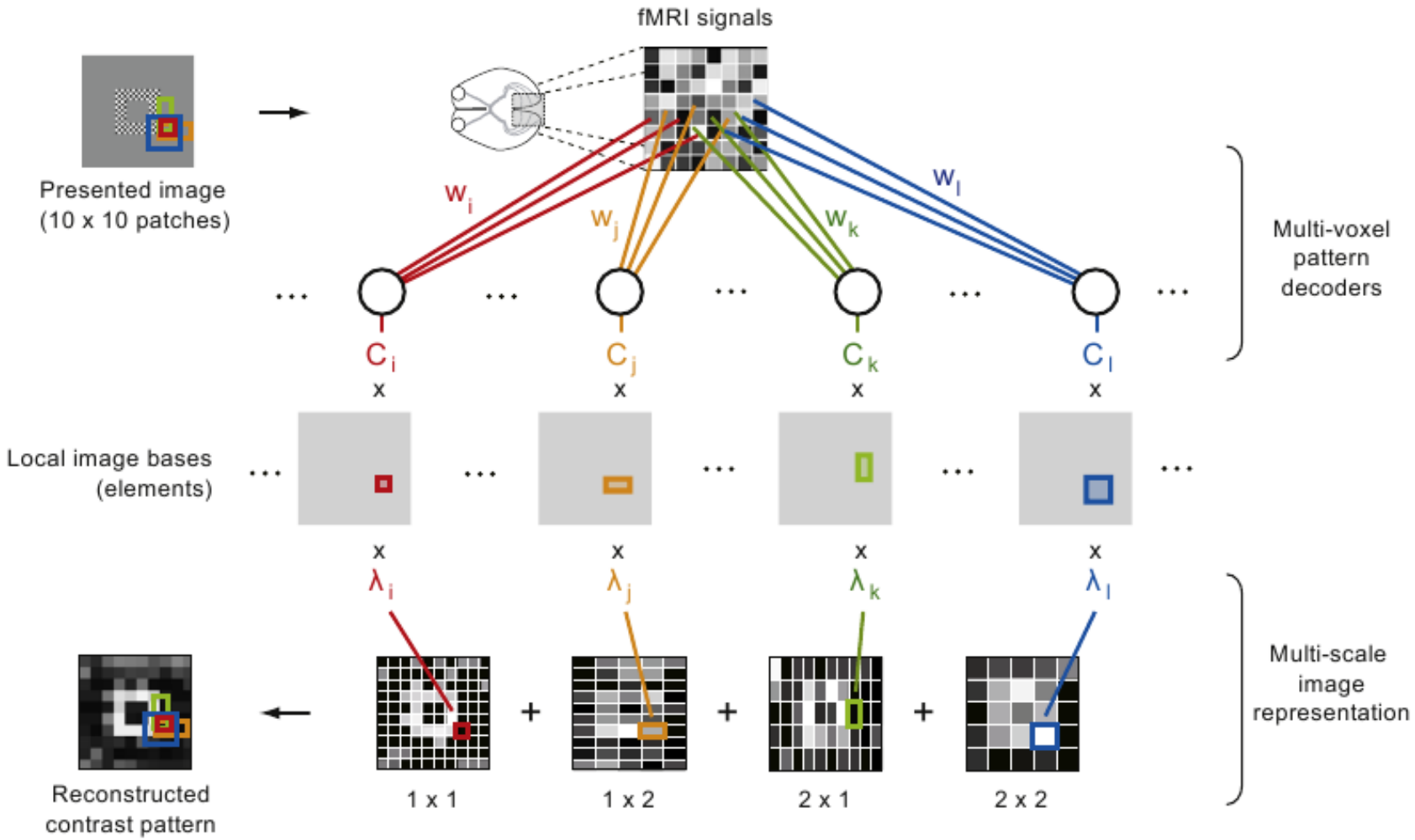
Different Levels of Decoding



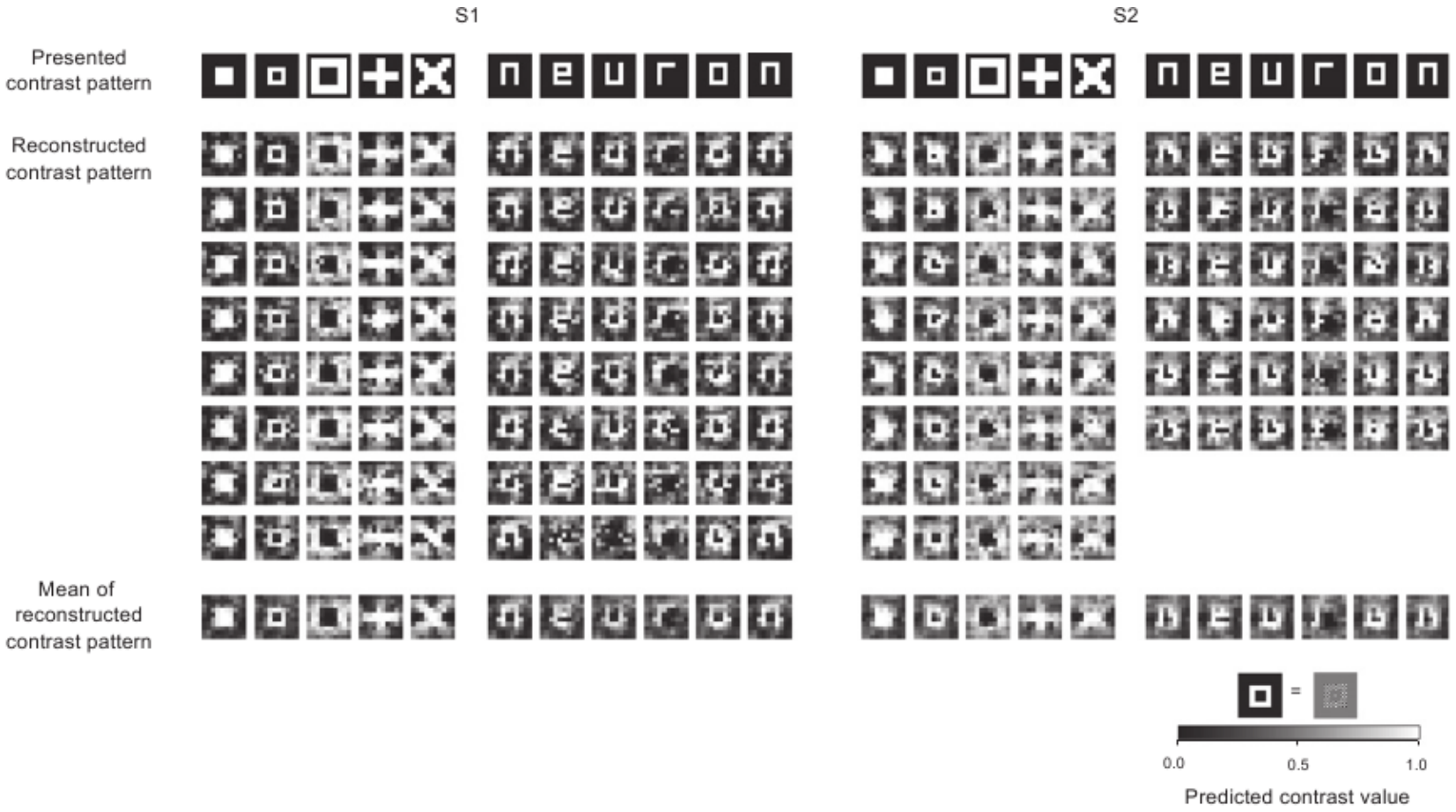

Stimuli Reconstruction
Decoder
?
Research Question
Experiment Design
Stimuli
Neural Processing and Encoding

Stimuli Reconstruction: Decoder

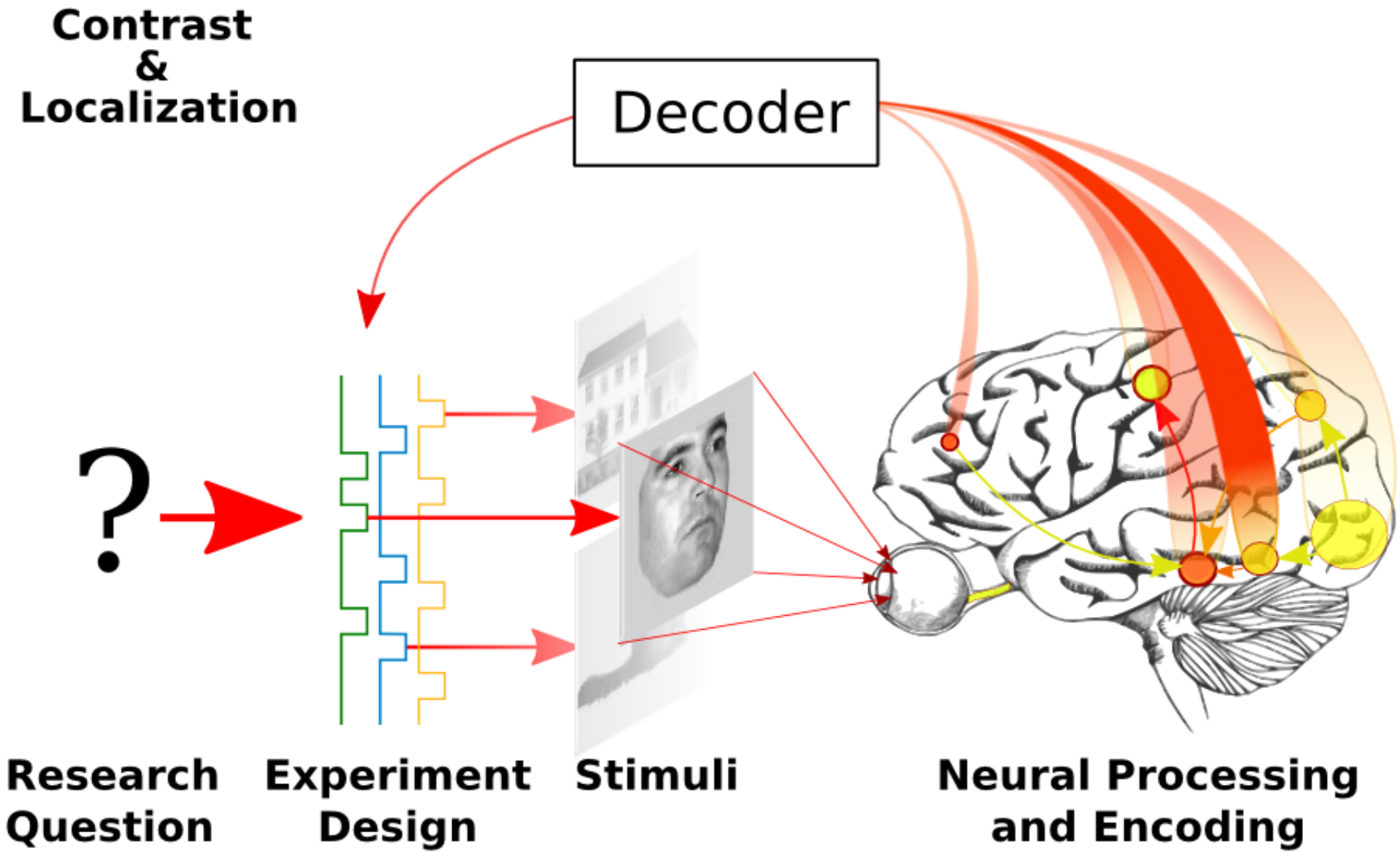


Miyawaki et al. (2008)

Stimuli Reconstruction: Results



Miyawaki et al. (2008)


Contrast
&
Localization
Decoder
?
Research
Question
Experiment
Design
Stimuli
Neural Processing
and Encoding

Analysis Strategies

Searchlight

- Run classifier on sphere-shaped feature clusters
- Retrieve spatial discriminance map (SDM)
- e.g. Kriegeskorte et al. (2006)

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Classify and dissect

- Run classifier on combinations of predefined ROIs
- Determine impact of each ROI by change in classifier error
- e.g. Pessoa & Padmala (2007)

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Classify and dissect

- Run classifier on combinations of predefined ROIs
- Determine impact of each ROI by change in classifier error
- e.g. Pessoa & Padmala (2007)

Knockout and classify

- Transform the data using PCA projection
- Remove components and compare change in error
- e.g. Carlson et al. (2003)

Sensitivity Analysis

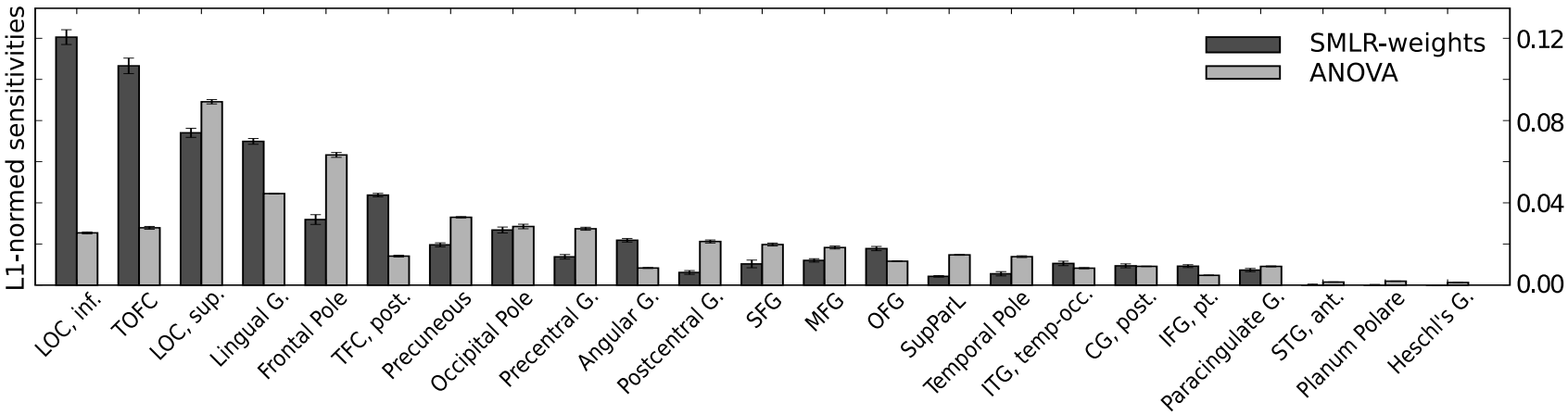
What is it?

- Not primarily generalization error-based
- Inspections of the ML model parameters
- e.g. Hanson et al. (2004)

Strategy

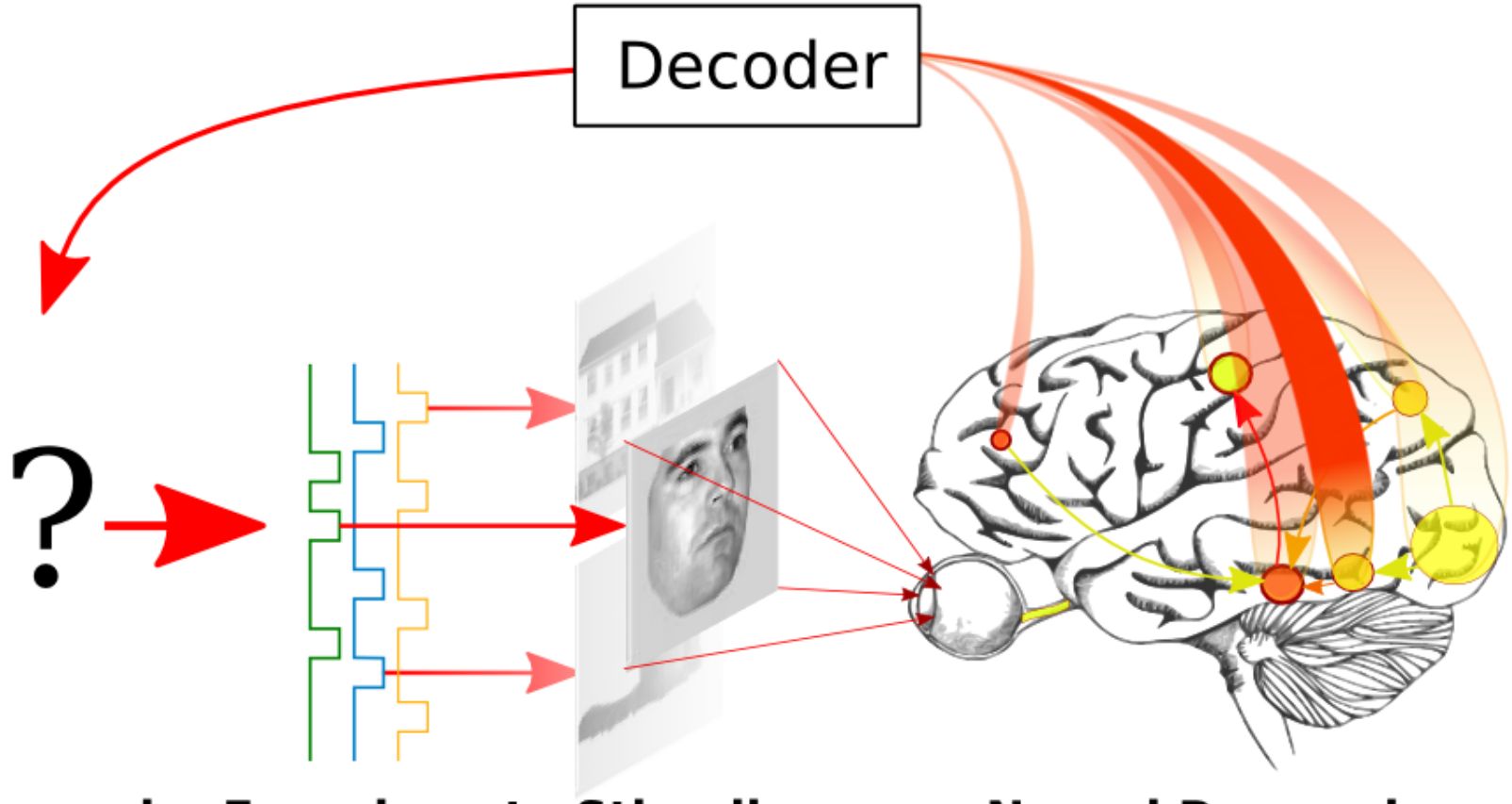
1. Preprocess the data
2. Train (fit) the model to the data
3. **Ensure the validity of the model (cross-validation)**
4. Extract model parameters/sensitivities and visualize them
5. Interpret the results

Sensitivity Analysis: 4 categories (SMLR)

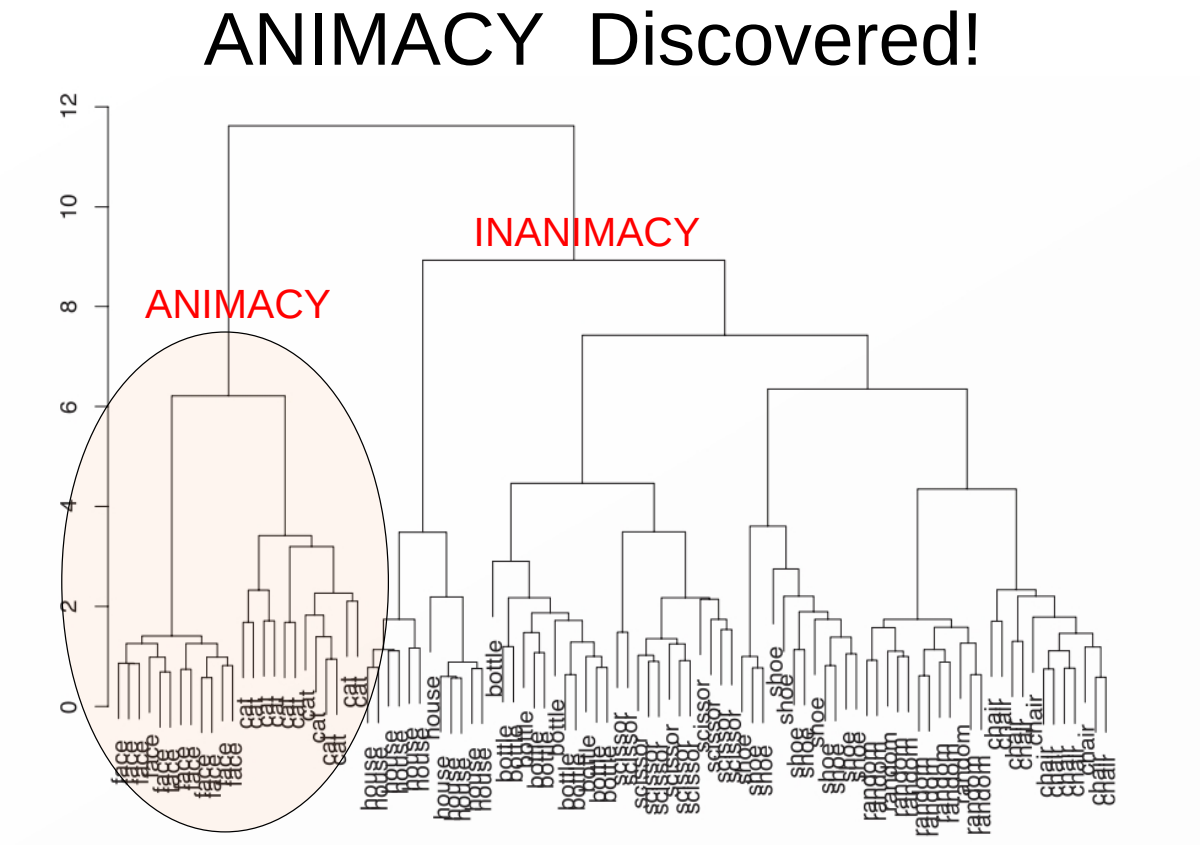


Hanke et al. (2009)

Explorative Analysis

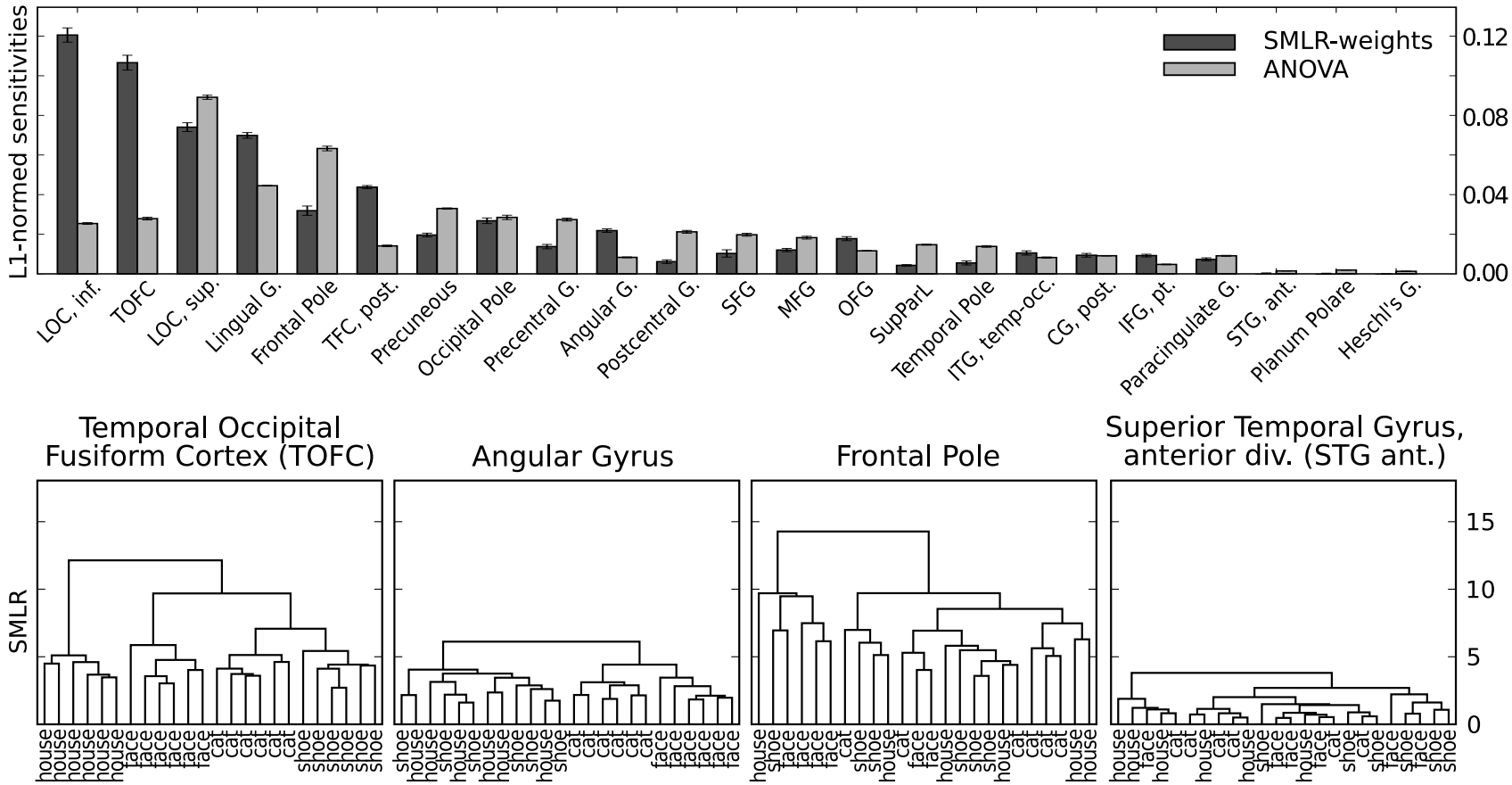


Exploratory Analysis: Previous Findings



Hanson et al. (2004)

Exploratory Analysis: Multiple Areas



Hanke et al. (2009)

Unimodal Analysis: Summary

Decoding approach . . .

- can reliably describe the behavior in terms of neural activity
- can be used across different neural data modalities at different levels of investigation
- cares about constructing reliable estimation
- allows to account for cross-trial variance and covariance structure
- provides super-acuity effect

Multimodal Neural Data Analysis

Promises

- Finer spatio-temporal resolution
- Improved detection power
- Improved stability of the results

Multimodal Neural Data Analysis

Promises

- Finer spatio-temporal resolution
- Improved detection power
- Improved stability of the results

Difficulties

- True neural signal is not known
- Unknown model of BOLD response
- Variability of BOLD across subjects and within the brain
- EEG signal distortion

Existing Approaches

- Correlative analysis
- Seeded or preconditioned E/MEG inverse
- Component analyzes
- Bayesian inference
- Dynamic systems models

Existing Approaches

- Correlative analysis

  $\Rightarrow$Rigid simplistic BOLD model, mass-univariate

- Seeded or preconditioned E/MEG inverse

  $\Rightarrow$Bias toward fMRI analysis results, E/MEG inverse problem, disregard of temporal evolution of fMRI

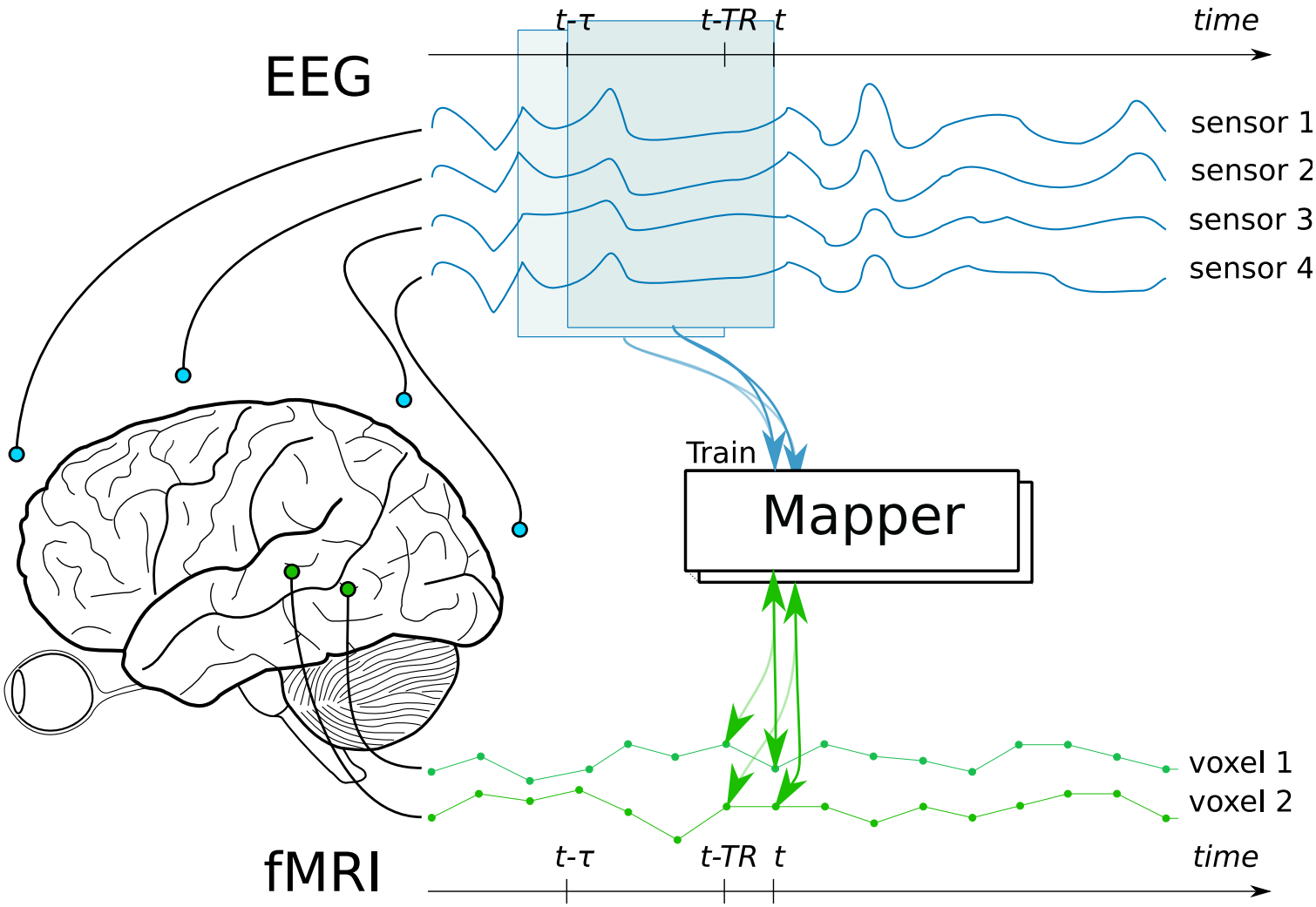
- Component analyzes

  $\Rightarrow$Rigid simplistic BOLD model, ad-hoc components matching

- Bayesian inference
- Dynamic systems models

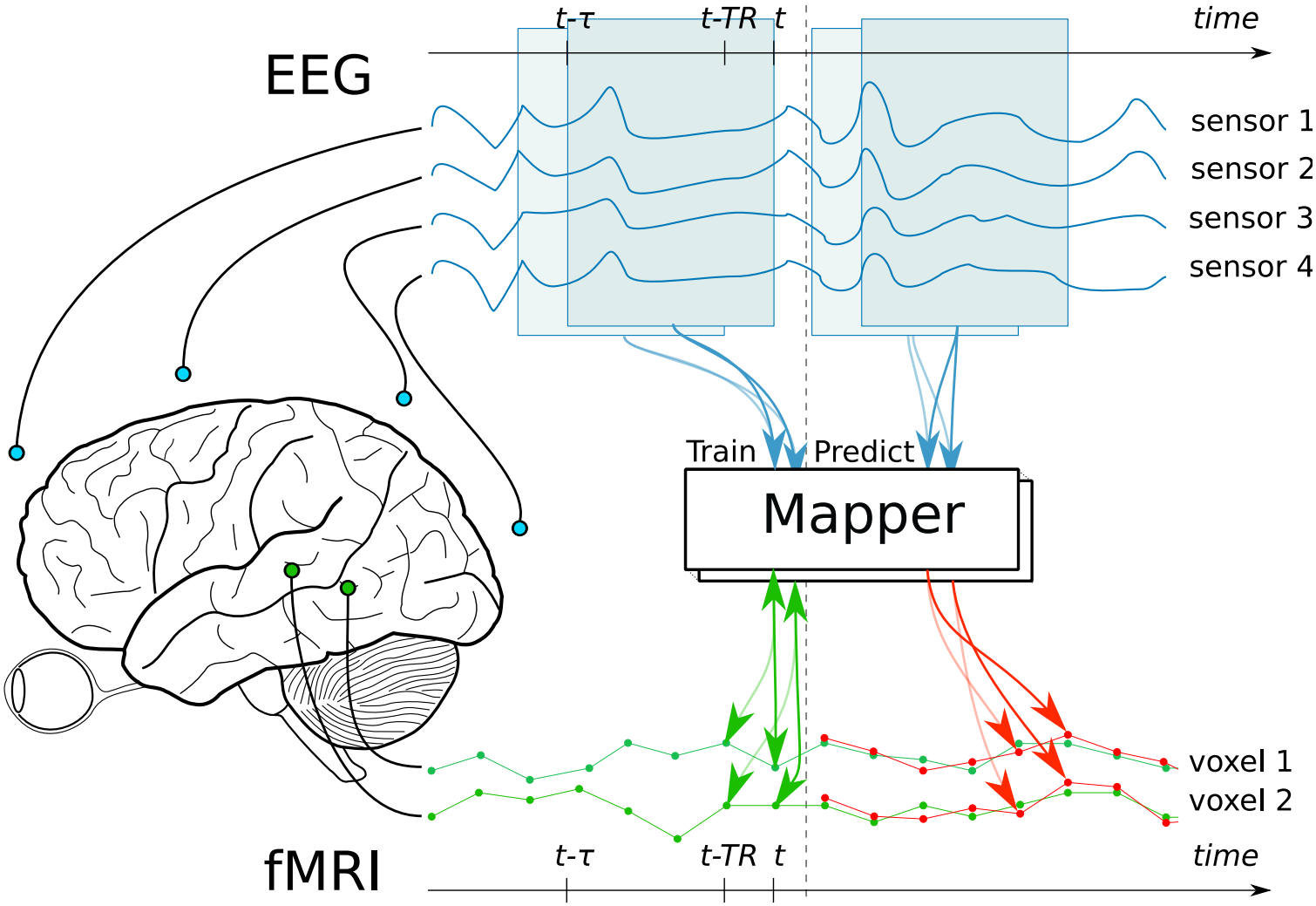
  $\Rightarrow$Simplifications to reduce parametrization

Methodology: EEG ⇒ fMRI



Halchenko (2009)

Methodology: EEG ⇒ fMRI



Halchenko (2009)

Real EEG/fMRI Data Analysis

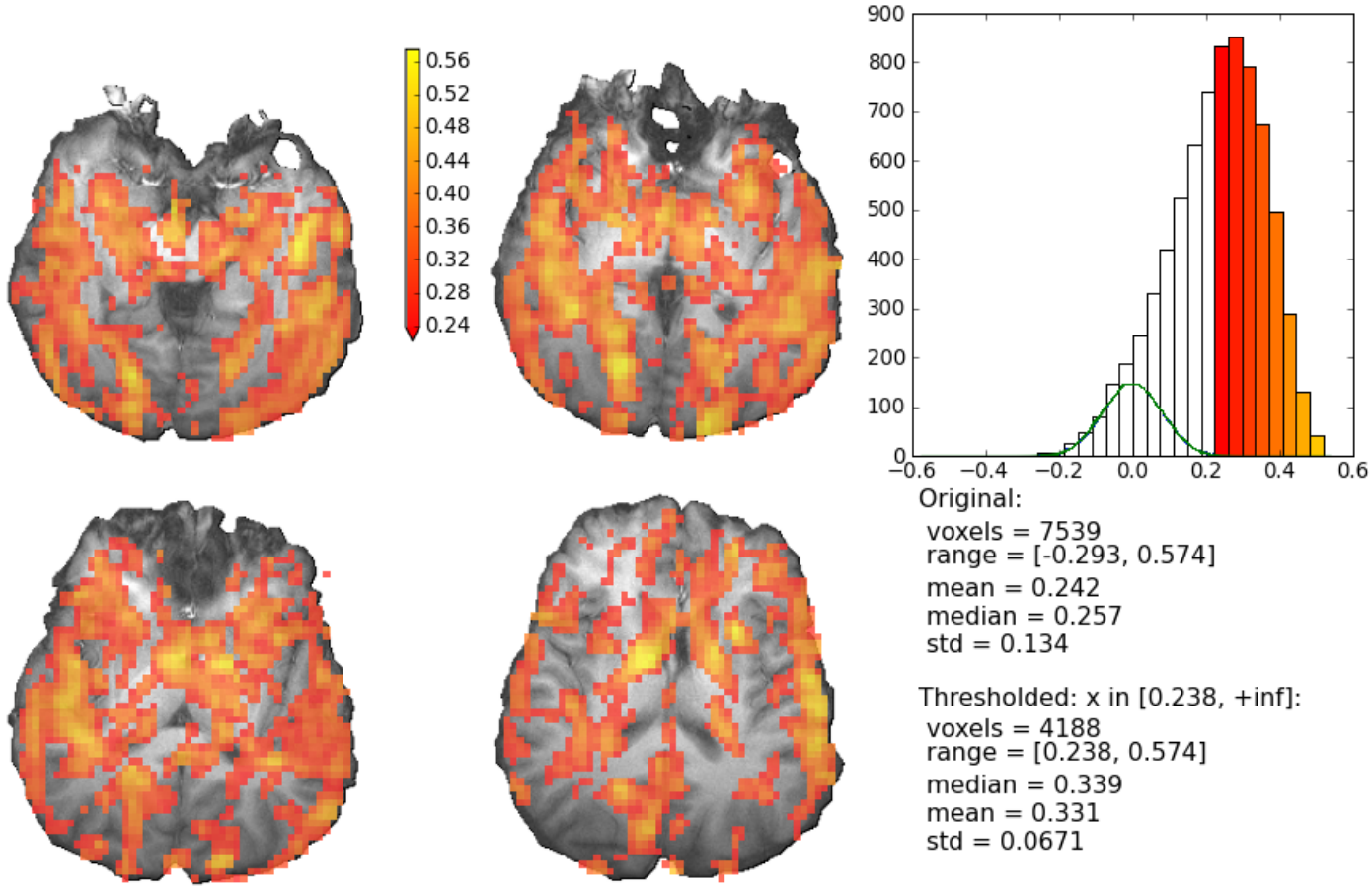
Experiment

- Auditory experiment (Thaerig et al., 2008):
  - Mono-aural stimulation
  - 2 levels of stimulation (60 and 80 dB)
- fMRI: FLASH sequence with 147 volumes at TR=11 sec
- EEG: 29 electrodes, corrected for MR-artifacts

Goals

- Validate the suggested methodology
- Localize the areas active during the task
- Localize the areas with dominant reliance on specific EEG rhythms

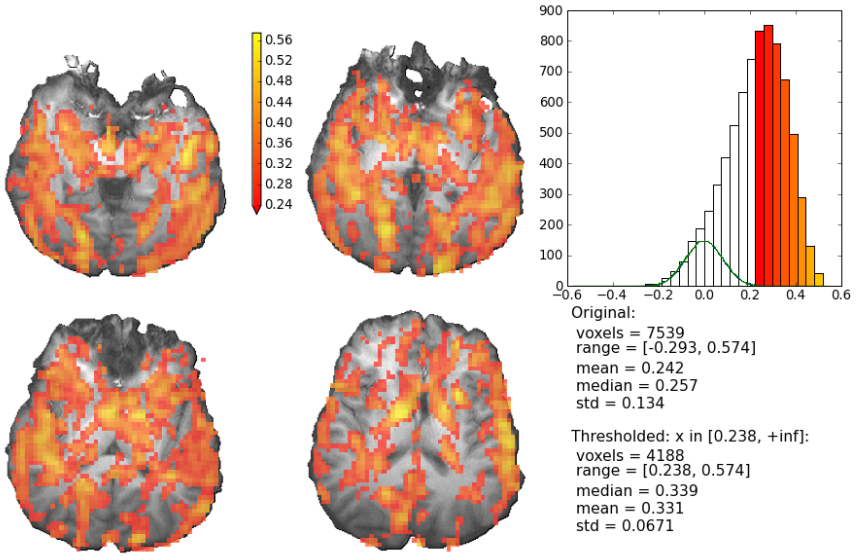
Multimodal Mapping



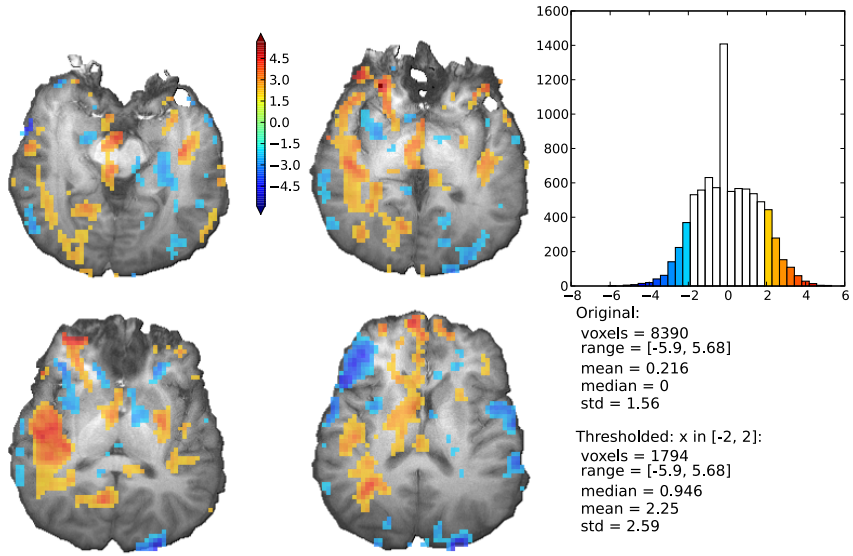
Halchenko (2009)

Multimodal Mapping: Compare to GLM

SVR Mapping

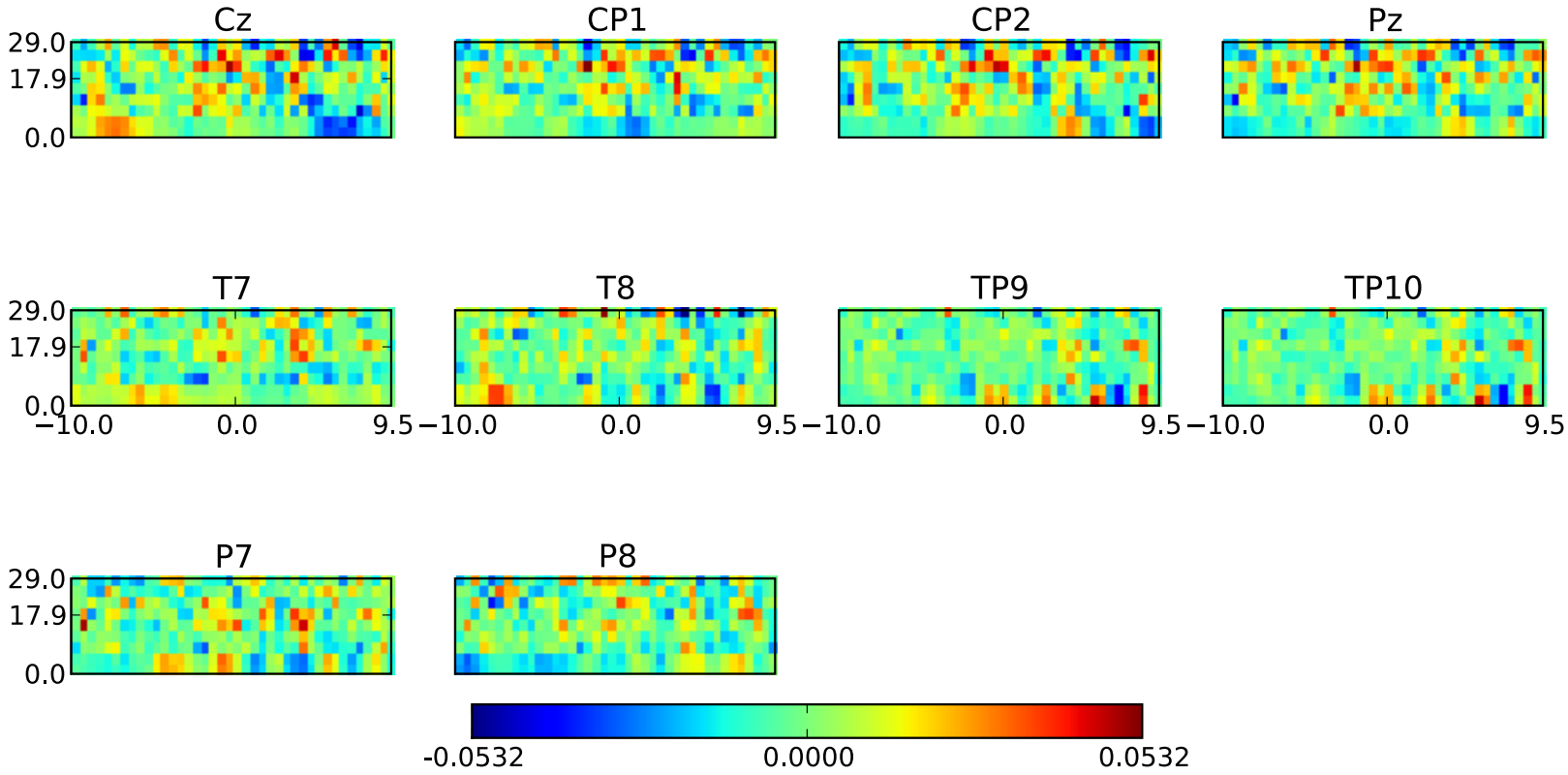


GLM



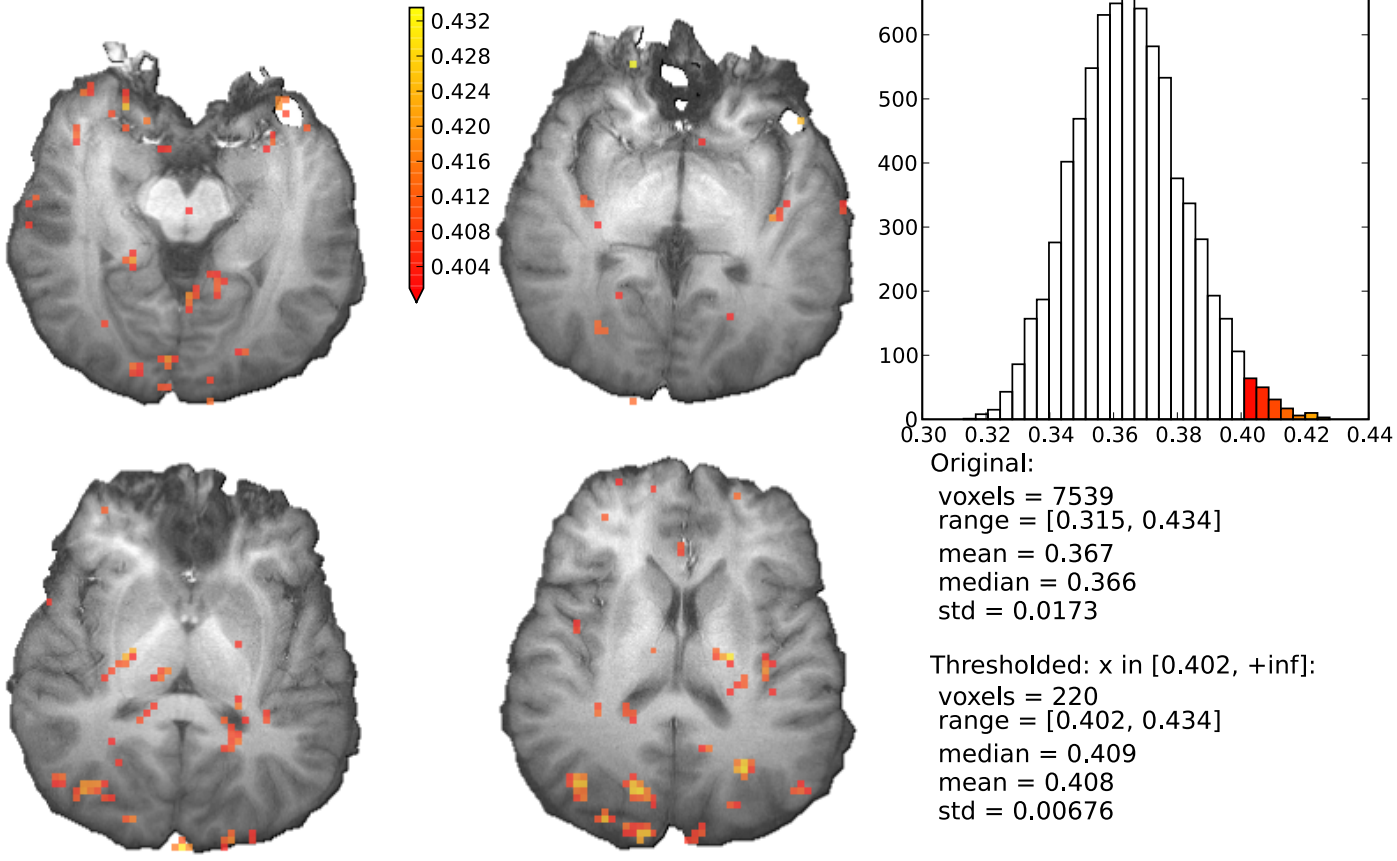
Halchenko (2009)

Sensitivity Analysis: Spatio-Temporal Profile



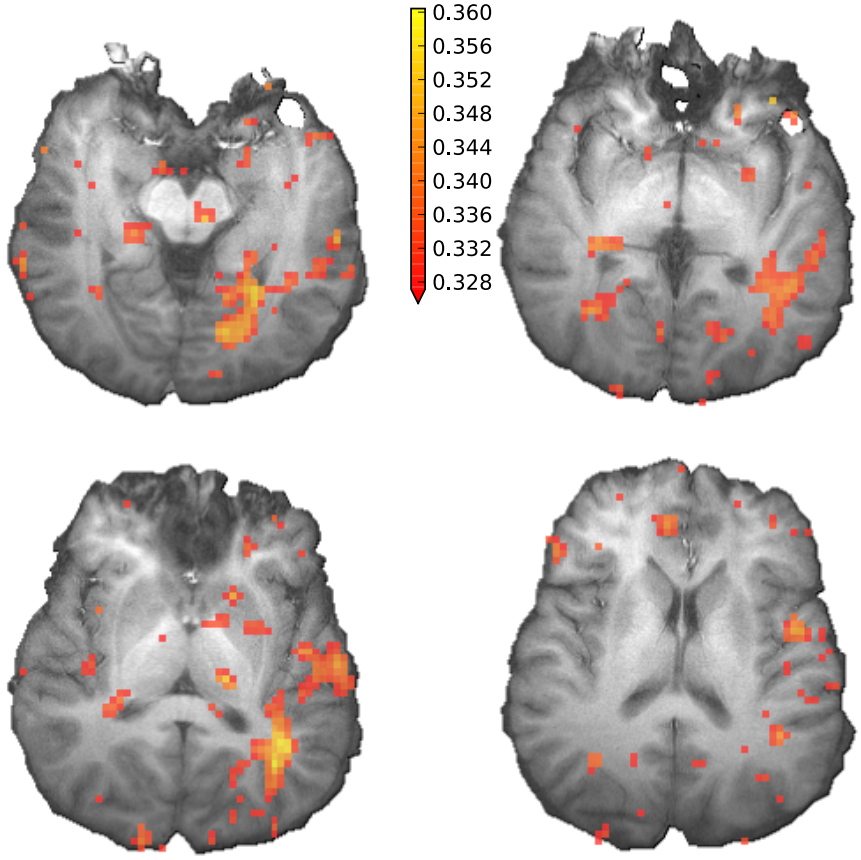
Halchenko (2009)

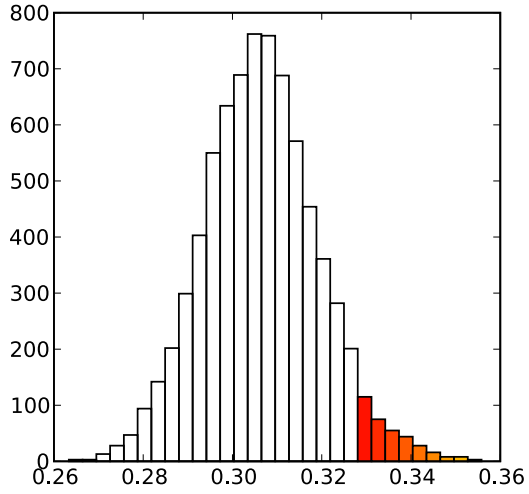
Sensitivity Analysis: α-band



Halchenko (2009)

T8 EEG Channel Sensitivities





Original:

voxels = 7539
range = [0.265, 0.36]
mean = 0.308
median = 0.308
std = 0.0128

Thresholded: x in [0.327, +inf]:

voxels = 510
range = [0.327, 0.36]
median = 0.334
mean = 0.332
std = 0.00644

Halchenko (2009)

Multimodal Analysis: Summary

- Validated suggested methodology on simulated and real EEG/fMRI data
- Provided localization of neural activity in the areas complementary to the results of GLM
- Provided localization for specific EEG rhythms

Additional Promises

- Interpolation of fMRI based on EEG
  - Boost of temporal resolution of fMRI
  - Improved slice-timing correction
- Filtering of fMRI and EEG

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Welcome Michael Hanke and PyMVPA!

Thank you